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Structure of the Jacksonburg Formation in Northampton and Lehigh Counties, Pennsylvania

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STRUCTURE OF THE JACKSONBURG FORMATION IN NORTHAMPTON AND LEHIGH COUNTIES, PENNSYLVANIA[1]

by William Cullen Sherwood[2]

ABSTRACT

The Jacksonburg Formation of Ordovician (Trenton) age crops out in the eat Valley Section of the Valley and Ridge Province in eastern Pennsylvania l western New Jersey. This paper reports on a field study of the structure of Jacksonburg in Northampton and Lehigh Counties, Pennsylvania.

The Jacksonburg is composed of limestones and argillaceous limestones, which, the area of study, have a maximum thickness of 1,150 feet. A conglomerate the base of the formation contains dolomite and chert pebbles, probably ived from the underlying Beekmantown group. The upper part of the forma-n grades into the overlying Martinsburg slate.

R. L. Miller (1937) divided the Jacksonburg Formation into two units; the nent limestone facies below and the cement rock facies above. In the present rk, the cement limestone facies is mapped as a single unit. The cement rock ies is subdivided into three mappable units: 1) the "argillaceous limestone" ich comprises the bulk of the facies, and interbedded with it, 2) the "lower stalline limestone" which occurs near the base of the argillaceous limestone, l 3) the "upper crystalline limestone" which occurs near the middle of the illaceous limestone.

Structural relations in the Jacksonburg indicate two distinct phases of de-mation. Recumbent, isoclinal folds of the first generation are the dominant ictural elements in the area mapped. One such fold which extends from aversville, Pennsylvania, to Ironton, Pennsylvania, is of sufficient magnitude be designated the "Northampton nappe". An axial plane flow cleavage appears be genetically associated with folds of the first generation.

Second generation folds are of two types: 1) large open folds, and 2) small-le crinkle folds. The second generation folds are superimposed homoaxially those of the first generation, deforming pre-existing bedding and flow cleavage. cleavage is genetically associated with folds of the second generation.

Major faults in the area are high and low angle thrusts with strike roughly allel to the trend of the formation. Cross faults of undetermined attitude offset beds and contacts at a number of localities. Normal faults were mapped in small area in the overturned limb of the Northampton nappe. Joints in the ksonburg are smooth, planar and uniformly steeply dipping. The dominant nt set strikes northeast-southeast.

Lineations are of two types: 1) lineations in the *b* or fold-axis direction, and 2) eations subparallel or parallel to *a*, the direction of transport. The *b* lineation he most common and includes the following: 1) intersections of cleavage and lding, 2) intersections of flow and slip cleavage, 3) axes of minor folds, 4) idinage, mullion and rodding, and 5) pyrite-grain elongation in bentonites. kensides and mineral streaking occur roughly parallel to *a*.

submitted to Lehigh University as a dissertation for the degree of Doctor of ilosophy.

presently a highways materials research analyst with the Virginia Council of ghway Investigation and Research.

It is suggested that the recumbent folds in the Jacksonburg were caused by graviting gliding. Two types of evidence are presented to substantiate this theory. These are: 1) configuration of the folds observed within the Jacksonburg Formation, and 2) general structural evidence from related areas not specifically covered in the present work.

INTRODUCTION

GENERAL STATEMENT

The Jacksonburg Formation of Ordovician (Trenton) age crops out in an irregular northeast-trending belt located in the Great Valley Section of the Valley and Ridge Province in eastern Pennsylvania and northwestern New Jersey (Fig. 34). That portion of the formation considered in this study extends some 30 miles from the Delaware River to the vicinity of Fogelsville, Pennsylvania (see Index Map, Fig. 1). This part of the Jacksonburg outcrop belt roughly bisects Northampton and Lehigh Counties, Pennsylvania, and includes portions of the following United States Geological Survey fifteen minute quadrangles: Delaware Water Gap, Wind Gap, Allentown and Alburtis.

This paper gives the results of a detailed study of the structure of the Jacksonburg Formation and contiguous parts of the underlying Beekmantown Group and the overlying Martinsburg Formation. On the basis of this study, the author proposes the presence of: 1) an early generation of recumbent isoclinal folds, possibly caused by gravitational gliding, and 2) a second generation of open folds homoaxially superimposed upon the older recumbent folds. A set of characteristic minor structures is associated with each type of fold.

GEOLOGIC SETTING

A generalized geologic map of the Great Valley Section in the area of study is shown on Figure 1. This section, known locally as the Lehigh Valley, is situated between the Reading Prong to the southeast and Kittatinny Mountain (the most easterly ridge of the Valley and Ridge Province) on the northwest (Fig. 34). The Jacksonburg belt approximately marks the centerline of the valley.

In Northampton and Lehigh Counties, the Great Valley is underlain wholly by a Cambrian and Ordovician sequence of sedimentary rocks (Fig. 2). That part of the valley southeast of the Jacksonburg belt is underlain by a sequence of older carbonate rocks, approximately 4,000 feet in thickness. The remaining half of the valley northwest of the Jacksonburg belt is underlain by argillaceous rocks of the younger Martinsburg Formation. The argillaceous limestones

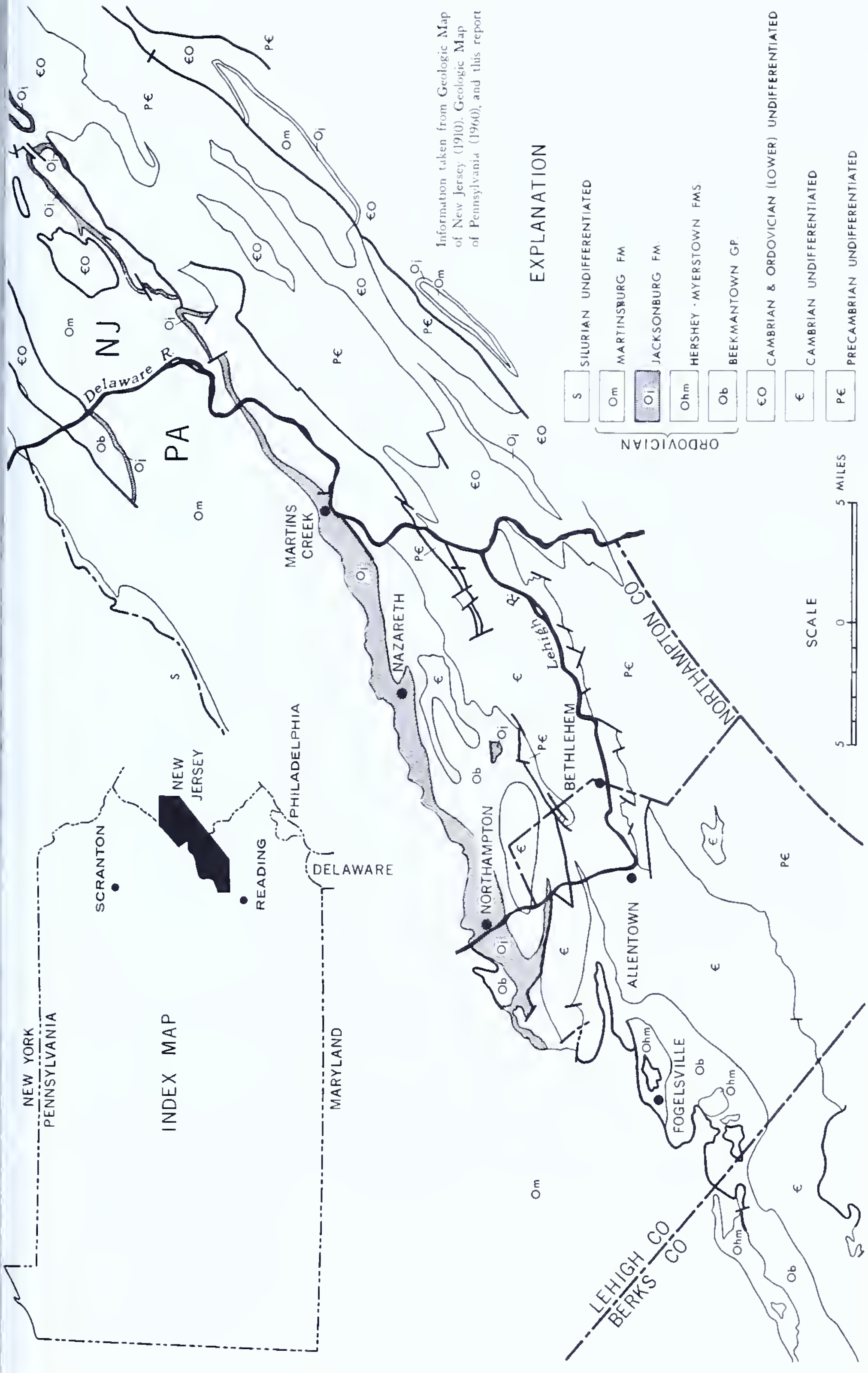


Figure 1. Index map of Pennsylvania showing location of area and generalized geology of Great Valley in eastern Pennsylvania and western New Jersey.

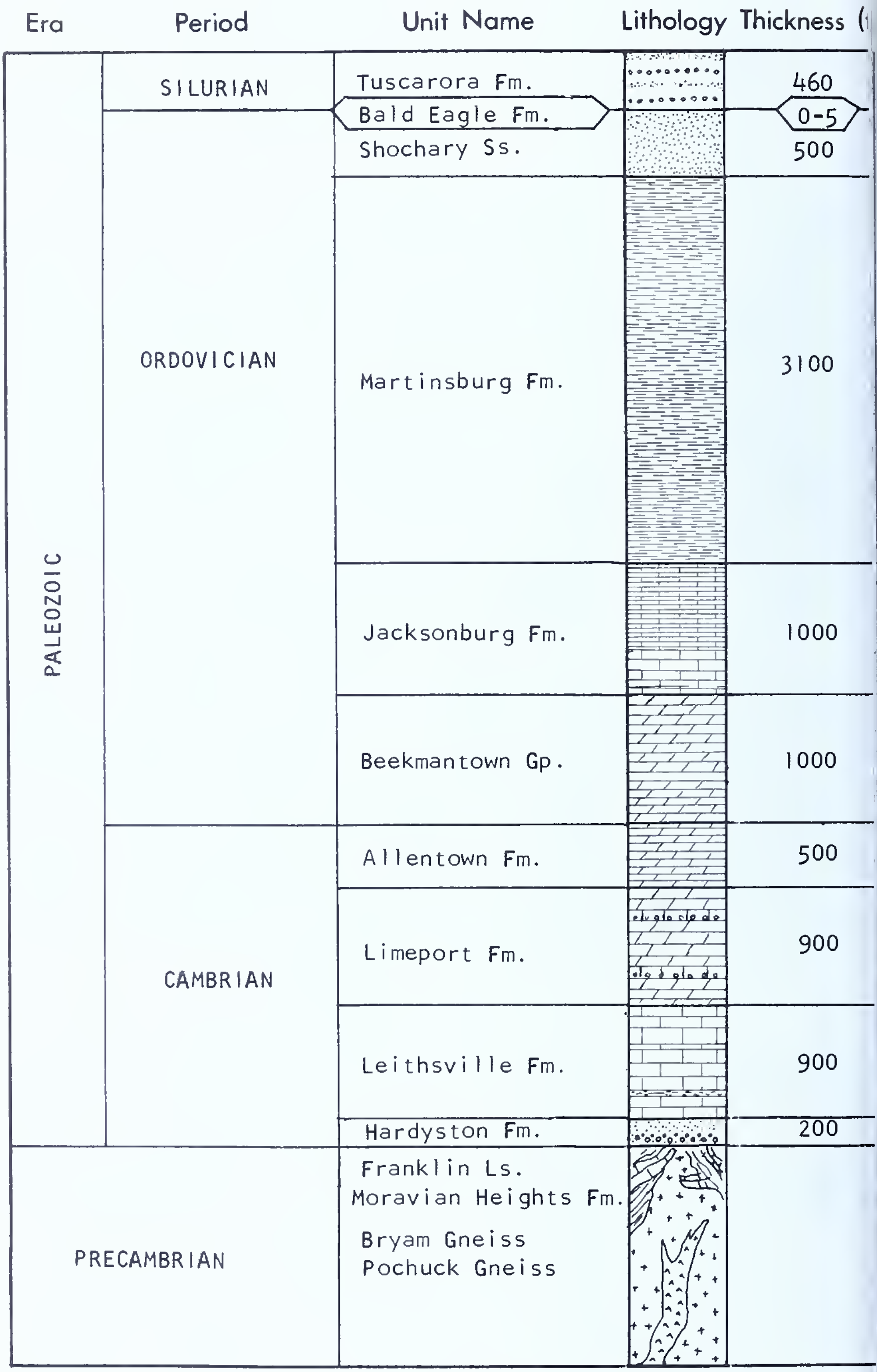


Figure 2. Generalized columnar section of rocks exposed in the Lehigh Valley in Northampt
and Lehigh Counties, Pennsylvania based upon B. L. Miller and others (1939, 1941), Swartz (194
Howell and others (1950), Willard (1947), and this report.

'f the Jacksonburg Formation may be viewed as a gradational equence representing a change from conditions favoring carbonate eposition to conditions favoring the deposition of terrestrially erived detritus.

'REVIOUS RESEARCH AND THE SCOPE OF THIS REPORT

The earliest published reference to the rocks of the Jacksonburg 'ormation as presently defined is that of Rogers (1858). Rogers riefly described the section at Martins Creek, measured the thickess as 350 feet and assigned it the formational name of Matinal mestone.

In the century following Rogers' first report, the outstanding work one on the Paleozoic rocks in the Great Valley of eastern Pennsylania and western New Jersey was largely stratigraphic. References) the rocks of the Jacksonburg Formation in New Jersey can be ›und in papers by Cook (1863, 1868), Kümmel (1900), Weller l903), and Spencer and others (1908). Reports dealing with the acksonburg Formation in Pennsylvania include those of Prime l878, 1883), Peck (1908), Wherry (1909), B. L. Miller (1925), ›ehre (1933), R. L. Miller (1937), and Prouty (1959).

Despite the excellent stratigraphic work done, few of these studies ›cused attention on the structure of the Jacksonburg and associated ›rmations in Northampton and Lehigh Counties. The present work an attempt to fill this need. The writer has remapped the Jacksonurg, determined the nature of contacts and subdivided the formation n the basis of lithology. Specific structural problems considered re: 1) type and extent of folding, 2) nature and origin of minor ructures and their relationship to major structures, 3) stress nplications and relationship of Jacksonburg structure to regional ructure.

METHOD OF STUDY

This report is based primarily on geologic field mapping. A total of ›ven months was spent in the field during the summers of 1959 and 960. Occasional trips to the area were made during the winters of 959–1960 and 1960–1961. Roughly fifty per cent of the field effort 'as devoted to mapping and collecting data from the large number f quarries in the area.

One of the problems encountered in the field was that of designing sampling program to collect data on the attitudes of minor strucıres. For this purpose the author made use of a design similar to ıat proposed by Pincus (1951).

Briefly, two routines were followed: 1) For minor structures which are plentiful over most of the area mapped (i.e. joints and flow cleavage), frequency quotas were set up so as to evenly saturate the area mapped. In quarries, where most of the data were collected, roughly equidistant stations were designated for data collection. 2) For minor structures found only in limited numbers (i.e. minor folds, slip cleavage and lineations) measurements were gathered where available with a limit of 5 for any single locality.

In a few localities, concentrations of readings on joints were gathered to represent limited areas. In order to show possible regional variation in orientation, the distance between such localities is at least ten times the maximum dimension of the locality. The data sources might then be considered as points.

Field studies were supplemented by studies of diamond drill cores and chemical analyses supplied by many of the companies operating in the area. Work in the laboratory included petrographic examination of forty-six oriented thin sections and a number of insoluble-residue analyses and X-ray-diffraction identifications of carbonate minerals and bentonite.

The terminology proposed by Folk (1957) is utilized in describing limestone and dolomite in thin section.

ACKNOWLEDGMENTS

The author is indebted to the late Dr. H. Richard Gault of Lehigh University, who suggested this study and aided in every aspect of the investigation and compilation, and to the many cement companies operating in the area for their willing cooperation in allowing access to their properties.

Support for this study has come from the National Science Foundation in the form of cooperative fellowships in the years 1959–1960 and 1960–1961.

The time and suggestions given by Dr. J. Donald Ryan of Lehigh University in the preparation and editing of the manuscript is greatly appreciated. Fruitful discussions in and out of the field were held with Mr. John Ames of the Alpha Portland Cement Company, Dr. Carl Warmkessel of the Lehigh Portland Cement Company, Dr. Carlyle Gray, former State Geologist of Pennsylvania, Drs. George R. Stevens and James L. Dyson, both of Lafayette College, and Dr. R. W. van Bemmelen of the Mineralogie-Geologisch Institut, Utrecht, Netherlands.

Finally, I would like to thank Kenneth D. Woodruff who ably assisted the writer in the field during the summer of 1960.

STRATIGRAPHY AND LITHOLOGY

GENERAL STATEMENT

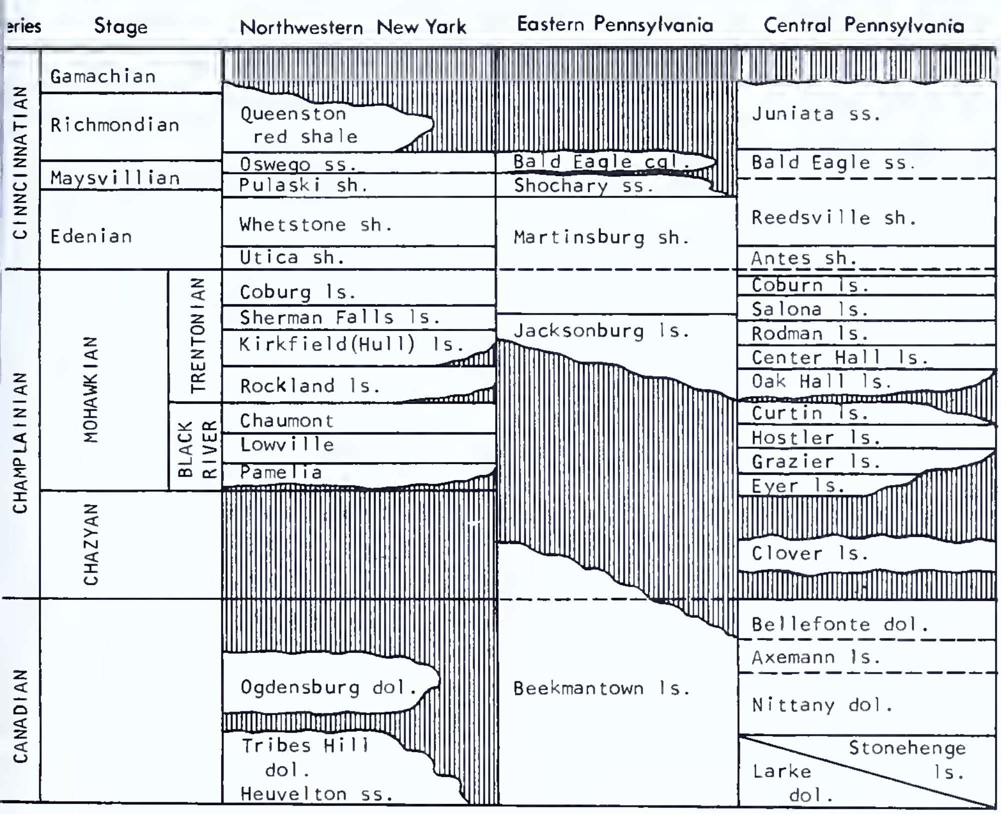
Rocks of Ordovician age in Northampton and Lehigh Counties iclude, from oldest to youngest, those of the Beekmantown Group, ie Jacksonburg Formation (unconformably overlying the Beekman-own), and the Martinsburg Formation (Table 1). The Bald Eagle onglomerate of late Ordovician age may or may not be present above ie Martinsburg. This report deals only with the Jacksonburg ormation and those portions of the Martinsburg and Beekmantown t or near the contacts with the Jacksonburg.

BEEKMANTOWN GROUP

Correlation

In eastern Pennsylvania, rocks referred to as the Beekmantown iroup (Hobson, 1963) consist of over 1,000 feet of dolomite and ibordinate amounts of interbedded limestone and chert. Correlation

'able 1. *Correlation chart of the Ordovician sections in northwestern Jew York, eastern Pennsylvania, and central Pennsylvania. Data from Junbar in Twenhofel (1954), Hobson (1957), Miller (1937), and this eport.*



of these rocks with those of the type section in New York State (Clarke and Schuchert, 1899) is not precisely correct. The term Beekmantown is retained in the present report with the understanding that no strict time correlation with the Beekmantown of New York State is implied.

Distribution

The Beekmantown Group in the Lehigh Valley crops out in an irregular northeast-trending belt two to three miles wide. The belt of outcrop is located immediately southeast of the Jacksonburg belt except in the vicinity of Egypt-Ironton and Fogelsville. In these areas, structural complexities cause Beekmantown to crop out north of part, or all, of the Jacksonburg.

Lithology

The Beekmantown section near the Jacksonburg contact is the only part of the Beekmantown which was studied in detail. In Northampton and Lehigh Counties, two distinct lithologies exist. East of Churchville, Northampton County (Plate 1), the Beekmantown consists of bedded dolomite with fairly abundant interbeds of limestone and chert and, in places, lenses of rounded quartz sand. West of Churchville the Beekmantown is largely a homogeneous sequence of bedded dolomite.

From Churchville eastward to Hope, New Jersey, the upper portions of the Beekmantown Group and the Kittatinny Formation (which underlies the Jacksonburg in New Jersey) contain increasingly more non-dolomitic beds. However, both east and west of Churchville, the blue-gray, very finely crystalline dolomite comprises the major rock type. The dolomite beds weather light brown in outcrop and typically have rounded edges. Fractures and thin quartz veins are abundant. Other carbonate beds in the Churchville to Hope area include medium-grained, light-gray, magnesian limestones, and impure saccharoidal limestones. The latter may look like conglomerate due to irregularities in color caused by weathering. Beds of black chert up to 1 foot thick and beds of sand and shale from 1 to 5 inches thick are commonly intercalated. This lithology is well exposed in the Sarepta quarry in New Jersey. In Pennsylvania, several feet of the section crops out in a small abandoned quarry two miles northeast of Martins Creek and in a railroad cut one-half mile northeast of the Lehigh Portland Cement Company plant at Sandts Eddy.

West of Churchville the thickly bedded, blue-gray, very finely crystalline dolomite predominates in the Beekmantown. Beds of limestone occur but are rare in most outcrops. No chert could be found in place. In only a few localities was this monotonous sequence

ound to show significant variation. One mile east of Weaversville, utcrops of conglomerate occur along the tracks of the Northampton nd Bath Railroad. In these outcrops, pebbles of dolomite up to 10 nches in diameter are found imbedded in a laminated, slightly nottled light-gray limestone. Black oölitic magnesian limestone and hert float were found at the Jacksonburg contact at Northampton. South of the Coplay cement plant, pure limestone beds near the top f the Beekmantown increase in number and thickness. Extensive nderground mining of these beds for high-calcium limestone was arried on for many years.

The lithology of the upper Beekmantown in the Lehigh Valley may e compared with the lithology of the Beekmantown section of the Schuylkill Valley as described by Hobson (1963). The dolomitic equence from Churchville westward resembles the upper and middle Ontelaunee (Hobson's uppermost formation). The more varied equence of interbedded dolomite, limestone and black chert in the astern part of the area mapped is similar to Hobson's lower Onte-aunee and the underlying upper Epler. These beds have been mapped s the Epler Formation by the United States Geological Survey in ecent work in the area (Avery Drake, oral communication).

JACKSONBURG FORMATION

Correlation

The Jacksonburg Formation in the Lehigh Valley is composed argely of dark-gray limestones and argillaceous limestones overlying he Beekmantown Group and underlying the Martinsburg Formation. As previously mentioned, the first description of these rocks was that of Rogers (1858), who referred to them as the Matinal limestone. Later Cook (1863, 1868), working in New Jersey, described outcrops of argillaceous limestone near the town of Jacksonburg and suggested correlation with the Trenton of New York. Kümmel (1900) used this designation in mapping these beds and recognized the presence of a basal dolomite conglomerate. Shortly thereafter, a detailed faunal and lithologic description of a section of these rocks was published by Weller (1903). Largely on the basis of this description, Spencer and others (1908) proposed the formational name "Jacksonburg."

Meanwhile in eastern Pennsylvania, Prime (1878, 1883) assigned a Trenton age to fossils from Rogers' Matinal limestone. Peck (1908), in studying the same rocks, used the formational name "Trenton" but divided the formation into the lower "limestone horizon" and the upper "cement rock horizon." Wherry (1909) recognized two divisions but referred to them as the "Nisky" and "Nazareth" Formations. B. L. Miller (1925) used the terms "cement limestone" and "cement rock." Behre (1933) correlated the formation with the type section at Jacksonburg but did not use subdivisions of the unit. R. L. Miller

(1937) conducted a detailed study of the stratigraphy of the Jacksor burg in New Jersey and Pennsylvania. He retained B. L. Miller' twofold division of cement limestone and cement rock but describe each as a facies. R. L. Miller's reasoning on this point is threefolc 1) at most localities, paleontological evidence for establishing tim equivalence of the separate facies is lacking; 2) the incursion of clasti material causing the change from cement limestone to cement roc was not contemporaneous throughout the area; and 3) intercalatio of the lithologies precludes the delineation of a sharp boundar between the two units.

Recently, Prouty (1959) correlated the cement limestone an cement rock facies of the cement belt with the Myerstown an Hershey Formations of the Lebanon Valley respectively. It is clea that the Hershey and Myerstown Formations occupy nearly the sam stratigraphic interval as the Jacksonburg Formation, and that th Hershey and Myerstown Formations of the Lebanon Valley grad lithologically into the Jacksonburg of the cement belt without shar demarcation. It is felt, however, that neither time nor rock equiva lency has been fully established. Therefore, the names Hershey an Myerstown are more appropriate west of the Schuylkill River, thoug they may be used east of the river wherever appropriate lithologie are established.

The latest evaluation of the age of the Jacksonburg Formatio (Cooper, 1956) assigns an age to the unit of middle and lower Trento (of Twenhofel and others, 1954).

Distribution

The belt of Jacksonburg outcrop in eastern Pennsylvania anc western New Jersey is shown on Figure 1. Only that portion of the Jacksonburg which forms the main outcrop belt in the Lehigh Valley was studied in detail. The irregular outcrop belt ranges from 0 to 2 miles in width. Variation in part is due to structural complexities which will be dealt with in subsequent sections and in part to non-deposition and erosion.

Four outliers of Jacksonburg were observed far removed from the main outcrop belt. In Northampton County an infold of Jacksonburg is situated south of the main belt at Hecktown and the faulted nose of a southwestward-plunging anticline exposes the Jacksonburg at Portland. In Lehigh County the Jacksonburg has been preserved in fault blocks in the Reading Prong at Lanark and north of Saucon Hill.

Lithology

Seven divisions in the Jacksonburg Formation can be recognized locally with the aid of chemical analyses and drill cores. However, only four divisions were found to be practical in field mapping.

These units are, in order of decreasing age:

1) The cement limestone facies of R. L. Miller, consisting largely of well-bedded calcarenite.
2) The cement rock facies of R. L. Miller (1937), consisting of the following three units:
   a) a sequence of black argillaceous limestone which extends from the top of the cement limestone facies to the base of the Martinsburg, herein designated the "argillaceous limestone";
      (1) a gray coarse-grained limestone within and near the middle of the argillaceous limestone, herein designated the "upper crystalline limestone";
      (2) a second coarse-grained limestone within the lower part of the argillaceous limestone, herein designated the "lower crystalline limestone."

CEMENT LIMESTONE FACIES

The cement limestone facies is composed of medium- to dark-gray, edded limestone which throughout the area mapped maintains a iickness of 275 to 375 feet. A basal conglomerate occurs in New ersey and in the eastern part of Northampton County. West of this ie lower contact is placed at the top of the uppermost dolomite bed.

In fresh exposures, the cement limestone is thickly bedded (beds up) 5 feet thick) and bedding planes are easily recognized. This feature particularly well exposed in the Nazareth Cement Company quarry Fig. 3). The rock is compact, ranges in color from medium gray to lack, and fractures into angular blocks. Hand specimens of fractured ock almost invariably sparkle in direct light due to reflections from ie cleavage surfaces of the larger calcite grains (up to 2 millimeters ı diameter).

Many of the thick beds contain thin argillaceous layers spaced everal inches to 1 foot apart, which are visible only in weathered xposures. Differential weathering of the argillaceous layers and the elatively pure limestone causes the more resistant limestone layers o project from the weathered surface, imparting a ribbed appearance o the rock. Further weathering causes disintegration of the argillaeous layers, leaving limestone slabs. Fossils stand out in relief on the lab surfaces. These weathered slabs occur at Alpha quarry No. 3 at Martins Creek where the best preserved Jacksonburg fossils in Pennsylvania have been collected.

The limestones of the cement limestone facies are calcarenites with llochemical grains ranging from .1 millimeter to 2 millimeters (Fig.). Allochemical constituents are about equally divided between ntraclasts and comminuted fossils. Cloudy carbonate particles devoid f diagnostic internal structure comprise the intraclast fraction.

Figure 3. Cement limestone facies. Note bedding is the dominant planar surface. Nazaret[h] Cement Company quarry, Nazareth.

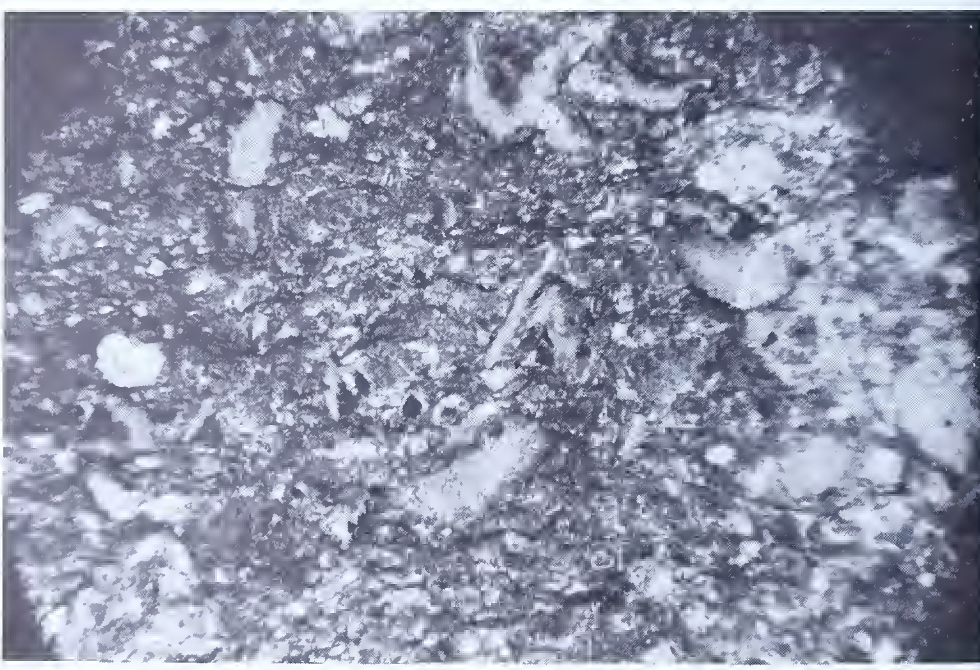


Figure 4. Photamicragraph of cement limestone. Note that texture is largely cataclastic[.] Irregular, black, horizontal lines represent trace of flow cleavage. X28

'ragments of bryozoa make up most of the recognizable fraction of he comminuted fossils. The orthochemical constituent is sparry alcite cement. The texture in all thin sections studied is cataclastic. Rotation, crushing, and recrystallization have obliterated the original edimentary features.

The total carbonate fraction of the cement limestone facies varies etween 70 and 90 per cent. X-ray and thin section analyses show olomite to be present in minor amounts. According to Ray and Gault 1961) the non-carbonate minerals in the Jacksonburg include quartz, eldspar, pyrite, non-graphitic carbon, illite, muscovite, chlorite and nontmorillonite.

Cement Rock Facies

As previously stated, the cement rock facies in the area studied can e subdivided into a thick argillaceous limestone unit with two nappable crystalline limestone units occurring within the argillaceous mestone sequences. These crystalline units are thickest in the eastern ortion of the area studied. As shown in Figure 5, the crystalline mestones thin and ultimately disappear westward. At Fogelsville nd west of Fogelsville, they are no longer recognizable.

The best exposed section of the cement rock facies in the area of tudy is located at Mud Run, 2 miles southeast of Martins Creek. 'his section traverses the Jacksonburg nearly at right angles to the trike and includes exposures in the quarries of the Lehigh Portland 'ement Company as well as exposures along the stream banks and oad cuts at Black Hill. The entire cement rock facies is estimated to e 830 feet thick in this section. The cement limestone-cement rock ontact, as is characteristic throughout the area, is conformable and radational. Basal conglomerate such as that reported at the base of he Hershey Formation in Lebanon Valley by Prouty (1959) is bsent.

Argillaceous Limestone.—Megascopically, the fresh argillaceous ement rock is a dark-gray to black, fine-grained, argillaceous limetone with pronounced flow cleavage (Fig. 6). Fragments broken cross the cleavage are dull gray. Cleavage surfaces may be black and listening due to concentrations of carbonaceous material and clay ninerals in layers parallel to cleavage. Bedding has been almost bliterated by the flow cleavage. Where discernible, the bedding is narked only by the presence of thin pyrite seams or slight color ariations. White secondary calcite fills many joints, faults, and other avities. The argillaceous limestone shows little lithologic variation hroughout the area mapped.

Weathering causes the argillaceous limestone to disintegrate into ray to buff plates. Even highly weathered plates retain sufficient arbonate to effervesce in acid.

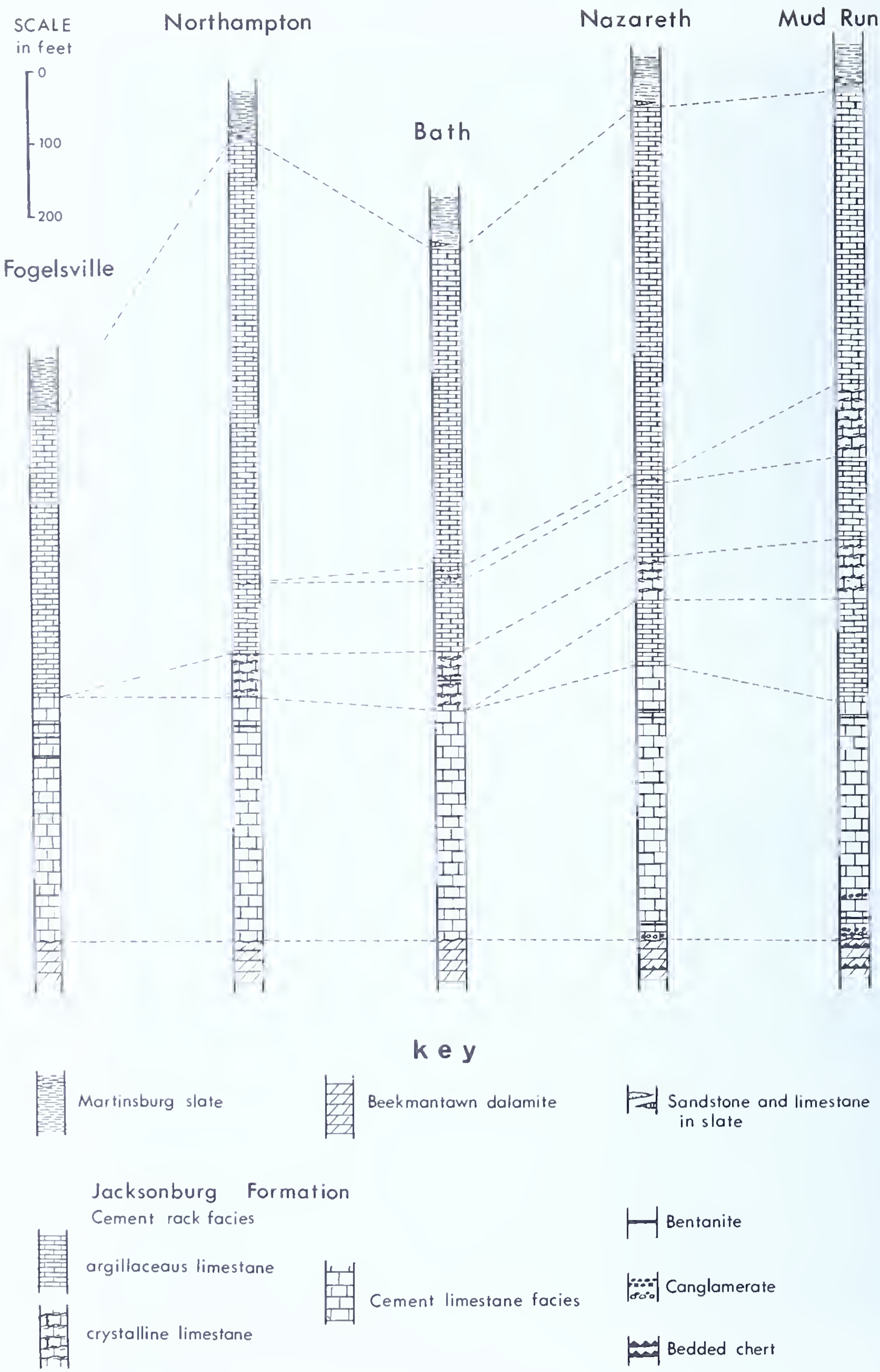
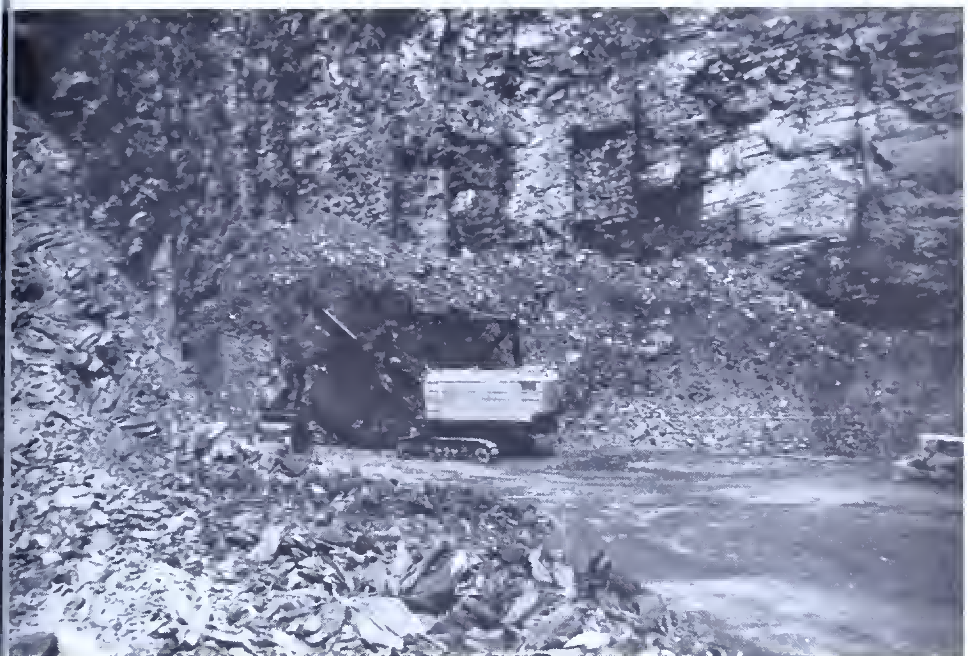


Figure 5. Calumnar Sectians af the Jacksanburg Farmatian in Narthamptan and Lehigh Caunties.



igure 6. Argilloceous limestone of the cement rock facies. S-planes in the upper right are / cleovoge. Coplay Cement Company quarry, Coplay.

Thin sections (Fig. 7) show the argillaceous limestone to be an pure calcilutite with grain size ranging from microcrystalline to 1 llimeter. The non-carbonate minerals have been studied by Ray d Gault (1961) using X-ray diffraction techniques and are listed in e previous section of the present work. Dolomite is reported by ıy (1957) to be present in the Jacksonburg where $MgCO_3$ comprises little as 2.5 per cent of the total rock. Chemical analyses from veral cement companies operating in the area mapped all show gCO_3 content of over 2.5 per cent for the argillaceous limestone, dicating that minor amounts of dolomite may be present.

A faunal zone characterized by the presence of large numbers of e Bryozoan *Prasopora orientalis* occurs in the argillaceous limestone out 40 feet below the lower crystalline unit at Mud Run. Individual lonies of this organism grow in the shape of a hemisphere with the anar surface oriented downward. This position would also appear be stable hydrodynamically, although evidence for reworking is sent. As a possible aid to geopetal relationships (i.e. indication of p and bottom of rocks at time of formation; Sander, 1936) in more formed areas, orientation counts were made on the individual lonies in the relatively undisturbed Mud Run section. Results of ese counts were as follows:

planar side down	81
planar side up	37

Figure 7. Photomicrograph of argillaceous limestone. Note fine-grained texture and parall arrangement of platy mineral grains, producing flow cleavage. XII

Figure 8. Lower crystalline limestone. Calcarenite interbedded with argillaceous limestone typical of this unit. Penn Dixie Cement Company quarry, Nazareth.

hose at appreciable angles to the bedding were not counted. A ıtistical testing of these data shows a significant preferred orienta- n (Sherwood, 1961, p. 27). It must be pointed out, however, that s sample represents the population in a single limited area and is t necessarily significant for other parts of the mapped area where undary conditions may be different.

Crystalline Limestones.—The two crystalline limestone units occur- g in the cement rock facies are lithologically similar except for the ghtly coarser grain size of the lower unit. Both are composed of ernating coarsely crystalline or marblized calcarenite beds from 1 20 inches thick intercalated with thinner shaly layers which emble the argillaceous cement rock (Fig. 8). The crystalline strata mottled, medium-gray and characteristically fracture perpen- ular to the bedding, yielding angular blocks.

On weathering, the shale layers disintegrate leaving large slabs of ystalline limestone. As in the cement limestone facies, fragments of sils may stand in sharp relief on the weathered surfaces.

The northeast wall of the Lehigh Portland Cement Company arry at Mud Run contains excellent exposures of both the lower d upper crystalline limestones. The lower crystalline limestone is feet thick. The bottom of the unit is 140 feet above the base of the nent rock facies. Succeeding the lower crystalline limestone is 150 t of argillaceous cement rock which, in turn, is overlain by the per crystalline limestone, here 105 feet thick.

Studies of thin sections indicate that allochemical constituents, nsisting of rounded intraclasts and fragments of fossils, are dominant the crystalline limestones (Fig. 9). The grain size as measured in in sections averages approximately 1.5 millimeters for the lower ystalline limestone and approximately .8 millimeters for the upper ystalline limestone. Clear calcite overgrowths developed in crystal ntinuity with the rounded grains are profuse. These may extend e grain radius an additional millimeter. Angular fragments of black gillaceous limestone up to several centimeters in size occur in the ystalline beds. These are oriented at various angles with respect to e bedding. Voids are filled with clear sparry calcite.

Beekmantown-Jacksonburg Contact Relations

A disconformity separates the Jacksonburg and the Beekmantown. nis disconformity represents the omission of most or all of Black ver and possibly some Chazyan time. The haitus at or near this vel apparently occurs over a great portion of the Appalachian stem and has been explained as due to the Blountian pulse (Kay, 42).

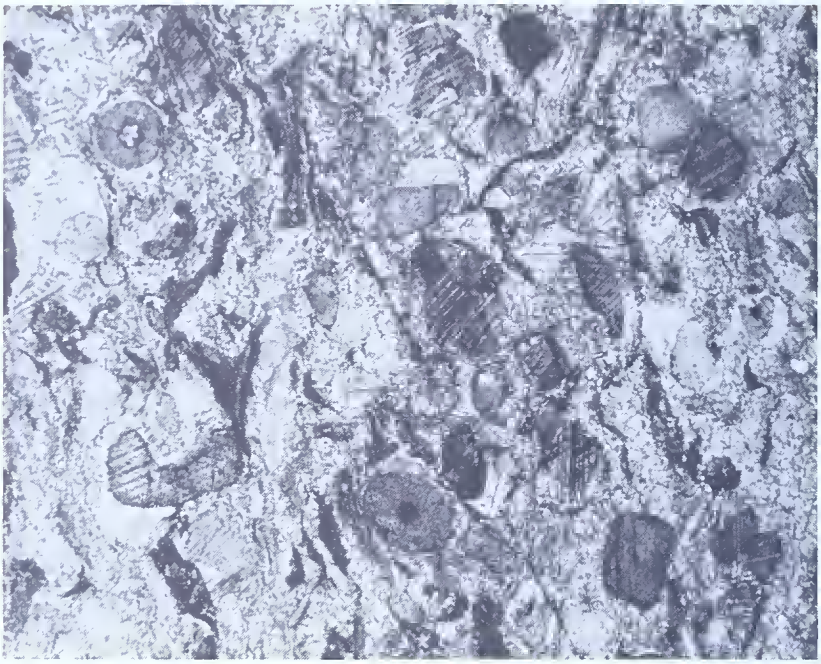


Figure 9. Photomicrograph of calcorenite from the lower crystolline limestone. Note the roun d intraclosts ond colcite overgrowths in optical continuity. X12

The writer has observed no angular divergence of strata above a below the contact. This relationship is clearly seen in the Sarep quarry at Sarepta, New Jersey; at the Trumbauer crushed sto quarry, one-half mile east of Nazareth, Pennsylvania; and at the No quarry of the Lehigh Portland Cement Company at Fogelsvil, Pennsylvania. In each instance, the contact is very abrupt b conformable.

Throughout the eastern part of the area mapped and in much the New Jersey outcrop a dolomite conglomerate occurs at the ba of the Jacksonburg Formation. This zone attains a maximum thic ness of over 100 feet in New Jersey and thins out rapidly westwa into Pennsylvania. It is about 5 feet thick at the entrance to t No. 4 quarry of the Lehigh Portland Cement Company at Sand Eddy and at the crossroads at Churchville. At the Trumbauer quarr, the conglomerate is absent, or at most, only a few inches thick. was not observed west of Nazareth, but has been reported by R. Miller (in B. L. Miller and others, 1941) as far west as Fogelsville a quarry section no longer available.

The conglomerate is a calcirudite. The greater part of the clast fraction is composed of pebbles ranging from .5 centimeters to centimeters in diameter. All the pebbles observed are gray, fin grained dolomite or black chert suggesting a Beekmantown sourc

The matrix is composed of medium- to dark-gray, fine- to medium-grained limestone which resembles the remainder of the cement limestone facies.

The eastward thickening of the Jacksonburg basal conglomerate is accompanied by a corresponding decrease in the thickness of the underlying Beekmantown Group. As noted earlier the Beekmantown lithology in contact with the Jacksonburg in the eastern part of the mapped area is more varied than that in the western part. This suggests possible absence of the upper Ontelaunee-type beds of Hobson in the east. Northeastward in New Jersey this relationship between 1) the increase in thickness of the conglomerate, and 2) the decrease in thickness of the pre-Jacksonburg rocks of Ordovician age, apparently reaches an extreme. R. L. Miller (in B. L. Miller and others, 1939, p. 260) states:

> In parts of New Jersey it (Jacksonburg) is believed to rest on Upper Cambrian beds, the Beekmantown having been completely removed by erosion.

Jacksonburg-Martinsburg Contact Relations

At every point where the Jacksonburg-Martinsburg contact was observed or inferred to be present, the writer interpreted it as conformable and gradational. This concurs with the observations of Weller (1903) in New Jersey and Behre (1927) in Pennsylvania. R. L. Miller (1937) reported slight angular divergence of strata on either side of the contact and suggested an agular unconformity. This does not appear to be the case in the area mapped.

An excellent exposure of the contact occurs on a steep high bank along the Bushkill Creek one mile northwest of Stockertown. At this locality, there is neither apparent angular divergence nor abrupt change in lithology. Insoluble residue percentages were determined for ten samples taken at intervals of 5 feet across the contact. These are compared with the percentages of insoluble residue measured by the Dragon Cement Company on samples from a drill hole 1,365 feet deep at Northampton. This hole passed from the Jacksonburg into the Martinsburg in an overturned sequence. The results of these analyses and the predicated break can be seen on Table 2. Three analyses of Martinsburg samples taken several hundred feet higher in the section show insoluble residues of 98.8, 96.3, and 96.1 per cent.

A similar contact zone is reported by R. L. Miller (in B. L. Miller and others, 1939). A drill hole (at 8b, Plate 1) was put down by the Universal Atlas Cement Company. In the top 200 feet of core the $CaCO_3$ content ranged from 58 to 72 per cent. At 200 feet the $CaCO_3$ content dropped to 38 per cent and decreased irregularly to a depth

Table 2. *Insoluble residues taken across the Jacksonburg-Martinsbur[g] contact at two localities.*

Bushkill Creek Area+ Outcrop Sample (5 ft. intervals)	% Insol.	*Dragon Quarry, Northampton** Hole Depth in Feet	% Insol.
10	87.4	870– 890	28.7
9	86.0	890– 920	28.2
8	85.1	920– 932	28.8
7	90.6	932– 940	32.4
6	86.4	940– 950	32.7
5	86.6	950– 970	39.3
4	80.1 Martinsburg	970– 990	41.0
. . . .		990–1000	34.7
3	57.0 Jacksonburg	1000–1032	59.7 Jacksonbur[g]
2	48.2	. . . .	
1	42.9	1032–1062	72.6 Martinsbur[g]
		1062–1083	75.9
		1083–1103	75.4
		1103–1139	78.7
		1139–1150	77.0
		1150–1180	88.1
		1180–1210	85.2
		1210–1230	86.6
		1230–1250	88.1

+ Section right side up.

* Section overturned.

of 245 feet. Here shale was encountered and maintained for a[n] additional 125 feet where drilling ceased.

Bentonites

Beds of bentonite are exposed in virtually all the major quarries i[n] the Jacksonburg Formation. The bentonite disintegrates when wet Most beds show well-developed cleavage. Field identification of th[e] bentonites was checked by X-ray diffraction studies. Strong mont-morillonite and quartz peaks were readily obtained.

Three of the bentonite beds can be traced with varying degrees o[f] confidence using one or more of the criteria proposed by Whitcom[b] (1932, p. 524–526). These beds include: (a) a pyrite-bearing bed, 6 t[o] 10 inches thick, which throughout the area of study occurs in th[e] cement limestone 20 to 60 feet below the cement limestone-cemen[t] rock contact, (b) a bed 4 to 6 inches thick which occurs 8 feet above the bed in (a), and (c) a bed 3 inches thick which occurs near the middle of the lower crystalline limestone. The bed described in (a) above was recognized at eight localities throughout the area mapped. The beds described in (b) and (c) were recognized at three localities.

MARTINSBURG FORMATION

Correlation

The Martinsburg Formation in the Lehigh Valley is composed of a thick sequence of slate and sandstone. This sequence is late Ordovician and upper middle Ordovician in age and was correlated with the Hudson River slates of New York State by the Second Pennsylvania Geological Survey (Lesley and others, 1883). The term "Hudson River slates" was also applied to these rocks in the same work. In the early part of the present century, the term Martinsburg came into widespread use and today it is almost universally accepted. The type locality is at Martinsburg, West Virginia, where the formation was described and named by N. H. Darton (1892).

Because of repetitious lithology and complex structure, the true thickness of the Martinsburg is in doubt. Estimates have ranged from as little as 3,000 to as much as 11,000 feet.

Distribution

The Martinsburg Formation crops out in a broad band 5 to 11 miles wide northwest of, and contiguous with, the Jacksonburg belt in Northampton and Lehigh Counties. The conformable contact with the underlying Jacksonburg, discussed in the preceding section, is continuous along the southeast border of the Martinsburg outcrop belt in Northampton County. In Lehigh County, the Martinsburg is in contact with the Beekmantown in limited areas (Plate 1). Structural complexities and non-deposition are suggested to explain the omission of Jacksonburg beds. These are discussed subsequently in this work.

Lithology

Only the lower several hundred feet of the Martinsburg was studied. This part of the formation consists largely of sericite-bearing blue-gray to gray slate called the hard slate member of the Martinsburg by Behre (1927). Cleavage is strongly developed. Individual beds range from 1 inch to nearly 1 foot in thickness. The beds may be recognized by slight color changes which according to Behre are due to variations in sericitic, siliceous and carbonaceous material. Graywacke beds, generally less than 2 inches thick, occur in the slates but are rare. Limestones up to 70 feet thick were mapped in the Martinsburg north of Weaversville, Northampton County. These are described in detail by R. L. Miller (1937).

On weathering the slate becomes light buff or tan and splits into thin plates. These plates characteristically make up a large percentage of the residual soil above the slate beds.

Behre describes a thin section of hard slate from the Chapman quarries as follows:

> Very few large grains of quartz are in evidence, and much of the groundmass is amorphous or so finely crystalline that under the crossed nicols the brilliantly colored calcite and muscovite stand out sharply from the dense, colorless background. The flakes of mica have an arrangement faintly suggesting fluidal texture. Two bands of darker material, evidently more carbonaceous beds, cross the field, and are separated by a width of lighter colored matter; the dark bands differ only in containing a large number of carbon masses. The light bands consist of: muscovite, quartz, carbon, calcite, chlorite, rutile and plagioclase.

STRUCTURAL GEOLOGY

GENERAL STATEMENT

The Jacksonburg outcrop belt in the Lehigh Valley is located in the northwest limb of a large anticlinorium, the core of which is partly exposed in the New England Province (Fig. 34). An adjacent large synclinorium lies to the northwest with its axis trending northeast-southwest through the Pennsylvania anthracite coal basins.

As early as 1858, Rodgers noted that the folds within this synclinal area generally are asymmetric or overturned to the northwest. Jacksonburg folds follow the regional trend and usually assume an even more extreme position—that of recumbency. Similar recumbency is also reported for folds deforming the Martinsburg Formation (Behre, 1927).

FOLDS

Description

A great variety of fold types occurs in the area mapped. These folds can be grouped into three categories on the basis of their appearance in cross section: 1) concentric folds, 2) similar folds, and 3) intermediate folds.

A summary of the occurrence and characteristics of each of these fold types as they appear in the Jacksonburg and contiguous formations is presented below.

1) Concentric folds (Figures 13 and 14)
   - Occurrence:
     - Limited to the Beekmantown and cement limestone facies
   - General characteristics:
     - Open folds, symmetrical to slightly overturned
     - Stratigraphic thickness maintained throughout fold
     - Voids and secondary filling caused by separation of beds in fold crests (see Fig. 30)
     - Slickensides in bedding planes, perpendicular to *b* axis

Orientation of minor folds related systematically to major folds
Boudinage and rodding fairly common
Wave length:
10^0–10^5 centimeters

2) Similar folds (Figures 10 and 12)
Occurrence:
Mainly in the argillaceous limestone of the cement rock facies and Martinsburg slate, locally in cement limestone
General characteristics:
Largely homogeneous lithology in a given fold
Notable thickening at the crest
Peaking of fold crests
Usually isoclinal and recumbent
Strong flow cleavage (S_2) slightly radiating or parallel to the axial plane
Marked directional fabric roughly parallel to axial plane
Digitations in fold limbs with axial planes parallel to S_2, but fold axes usually bear little systematic relationship to major folds
Wave length:
10^0 to 10^4 centimeters

3) Intermediate folds (Figure 11)
Occurrence:
Generally in the bedded limestones of the cement limestone facies and in the crystalline limestones of the cement rock facies
General characteristics:
Virtually all of the characteristics attributed to both flexural slip and cleavage folds may be present
Overturned to recumbent
Bedding planes well preserved despite moderate to strong axial plane cleavage
Slightly isoclinal with rounded crests
Minor folds usually related systematically to the major folds
Wave length:
10^0–10^4 centimeters

In addition to their physical characteristics, folds occurring in the Jacksonburg may be classified chronologically as "first generation folds" and "second generation folds." First generation folds are defined as the first folds to deform a sequence of strata as interpreted by the writer. These consist of a large-scale recumbent fold or nappe and associated recumbent digitations. All folds superimposed on this

previously folded sequence are herein considered second generation folds. Second generation folds include large open folds and smaller crinkle folds.

First Generation Folds

Nappe Structure

A large-scale recumbent anticline, or nappe, overturned to the north and northwest, is the dominant structural feature in the area mapped (see cross sections, Plate 1). The essential elements of the nappe, herein designated the Northampton nappe, are best exposed in the area from Weaversville, Northampton County, westward to Ironton, Lehigh County. The inverted sequence in the vicinity of Ironton was recognized in earlier work on the area by B. L. Miller (1941) and Willard (1958). The Northampton nappe apparently plunges at a low angle to the northeast, since east of the area delineated above, only the upper or normal limb of the structure appears at the surface. West of Ironton, outcrops of Jacksonburg are discontinuous and structural relationships are obscure. The isolated outlier of Beekmantown north of Egypt is interpreted as an infold of the dolomite core of the nappe. This infold occurs due to folding in the nose of the nappe beyond 180°. Digitations of the similar-fold type bearing systematic relationship to the parent fold are common in the cement rock facies. Other evidence bearing on the existence of the Northampton nappe is presented in the following discussion. Stations referred to in the text are inscribed on Plate 1.

Northampton County.—Bedding in the entire eastern half of the mapped area, excluding small local variations, shows a general similarity of attitude. This general homogeneity extends from the Delaware River on the east to approximately one mile west of the hamlet of Jacksonville. Throughout this belt the regional dip is to the northwest and the beds are right side up. Flow cleavage is nearly horizontal or dips gently to the south or southeast.

Bedding-cleavage relations indicate this sequence to be the upper limb of a large overturned anticline or nappe structure. Digitations on the limbs of the fold also point to this interpretation. West of Jacksonville, what appears to be the nose and lower limb of the structure appear at the surface. The question then remains as to whether this eastern area is underlain by a structure of true nappe magnitude as indicated in the Northampton-Ironton area or by smaller scale plications.

In the vicinity of station 1 (Plate 1), 2 miles northeast of Churchville, drilling indicates that an unusual degree of deformation has disrupted the strata. Faults and southward dips were also encountered (Dr. Carl Warmkessel, oral communication). These data, together

with the notable increase in outcrop width at this point may be indicative of large-scale overturning.

Station 2 marks the approximate position of a core hole on Bushkill Creek one-half mile north of the Hercules Cement Company plant. The hole was collared in Jacksonburg. At a depth between 200 and 300 feet, the hole entered Martinsburg slate and encountered only slate to the bottom of the hole (50 feet below the contact). Two interpretations are suggested as possible causes for this inverted sequence: 1) the hole passed through the eroded nose of a large recumbent anticline, or 2) a fault has brought Martinsburg back under the Jacksonburg outcrop belt.

These irregularities encountered during drilling, together with the data from minor structural features described earlier (cleavage-bedding, digitations) strongly indicate that the entire eastern portion of the outcrop belt represents an exposure in the normal limb of a large recumbent fold.

Cross section A-A′, along Mud Run, shows the typical structure encountered in this eastern area. The normal sequence dips monoclinically to the northwest. Steepest dips, on the order of 42°NW, occur at the Beekmantown contact. These decrease to less than 20° NW at the middle of the section. Small scale recumbent folds or digitations with anticlines pointed to the northwest occur near the contact in both the Jacksonburg and Martinsburg (Fig. 10).

Between Mud Run and Nazareth no essential change in structure is evident at the surface. Section B-B′, representing the section along the east edge of Nazareth, illustrates a similar monoclinal dip free of the major disrupting influences. The faulted, plunging syncline to the south is local in extent, reflecting an unusually steep plunge of the fold axis rather than any basic change in the major structure.

A radical change in the outcrop pattern of the Jacksonburg takes place to the west, between Knauss School (2 miles west of Jacksonville) and the town of Northampton on the Lehigh River. This pattern suggests that a northeast regional plunge has brought to the surface the nose and inverted limb of a large recumbent fold or nappe. Evidence for the existence of this nappe is discussed below.

Station 3—The maximum width of the Jacksonburg belt (approximately 2 miles) is at this locality. Elsewhere, the belt generally is less than 1 mile wide. In view of the consistently high dips measured on bedding ($>30°$) throughout much of this section, the anomolous increase in width of the outcrop belt strongly suggests repetition of beds.

Station 4—The faulted infold of Jacksonburg 1¾ miles south of the main outcrop belt, further points to the absence of simple monoclinal folding.

Figure 10. Nose of a recumbent similar fold in the argillaceous limestone. Note thickened fold crests relative to fold limbs and the presence of axial plane flow cleavage. Road cut 1 mile NW of Sondts Eddy.

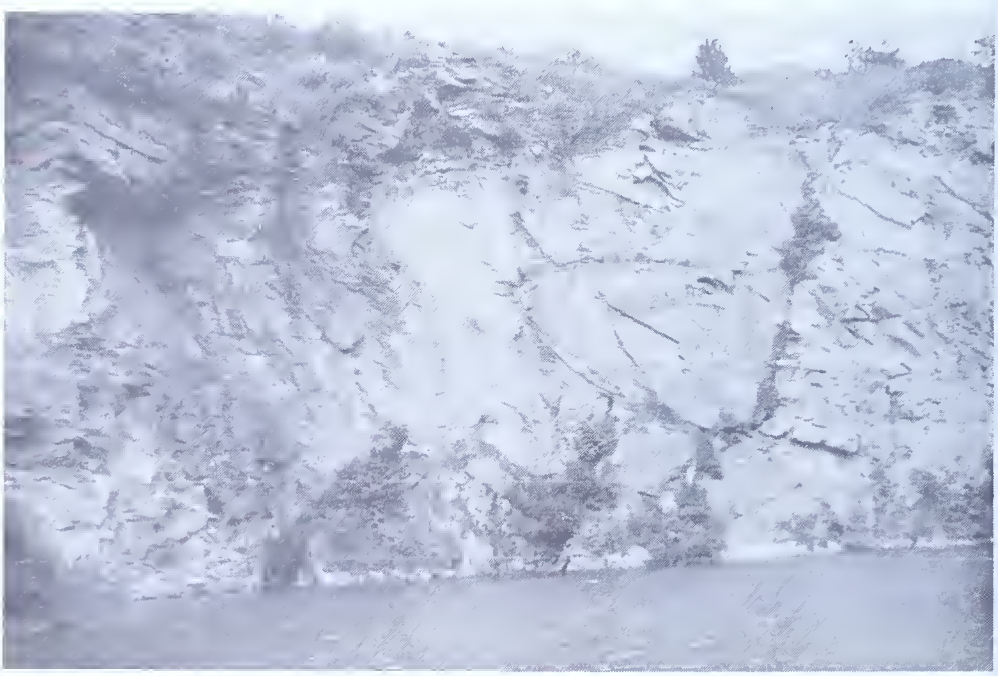


Figure 11. Recumbent fold in the cement limestone. Fold shows both similar and concentric characteristics. Note the bentonite bed wrapping around the fold. Abandoned quarry, Coplay Cement Company, Coplay.

Station 5—Absence of strong notching in valleys along the Martins-burg contact indicates that the dip is considerably steeper here than o the east. This could be due to the emergence of the nose of the ecumbent structure.

Station 6—Dips along the Jacksonburg-Beekmantown contact are argely to the south. This direction of dip shows that the Jacksonburg nderlies the Beekmantown probably in an overturned sequence.

Station 7—Additional evidence of overturning in this area is btained from fossil orientation counts. Station 7 marks the location f an abandoned quarry owned by the Universal Atlas Cement Company. Counts on the orientation of *Prasopora* specimens indicated wenty-three inverted and eight upright. Tests showed these data to ave a significant preferred orientation (Sherwood, 1961, p. 46).

Stations 8a and 8b mark the locations of drill holes which passed hrough the Jacksonburg and into the younger Martinsburg. At 8a hole drilled by the Dragon Cement Company) the contact is grada-ional (see Table 2) but can be drawn with fair accuracy at 1,000 feet. The hole at 8b was drilled by the Universal Atlas Cement Company. A description of this core is given by R. L. Miller (in B. L. Miller and others, 1939) and reviewed in this work under "Jacksonburg-Martinsburg contact relations." The hole in the Atlas property appears to be particularly significant in regard to the proposed nappe heory, as it occurs south of the hole drilled by Dragon, yet en-countered the slate at a shallower depth. It is also significant that no consistently high values of $CaCO_3$ content indicating the presence of he cement limestone facies were obtained in these holes (see cross section C-C′).

Stations 9 and 10—Unusually severe deformation of both the Jacksonburg and Beekmantown can be seen at these exposures. Station 9 is located at the active quarry of the Dragon Cement Company. Crumpling, fracture, and rehealing with secondary calcite and quartz is intense. Severe deformation in the Beekmantown occurs at Station 10 and extends westward as far as Ormrod, Lehigh County.

The entire exposed section at Northampton appears to be over-turned (see cross section C-C′, Plate 1). Cement limestone has been removed by erosion, except at the Beekmantown contact. This is substantiated by analyses of the core from drill holes at 8a and 8b. With a slight plunge eastward it is clear that in this direction only the normal or dotted limb of C-C′ would be exposed at the present land surface.

Lehigh County.—Structural evidence bearing on the Northampton nappe can be traced west of the Lehigh River as far as Ironton. At Ironton a fault apparently has dropped the overturned limb down so that the Beekmantown is still preserved over the Jacksonburg. West

of Ironton, and east of the point where Jacksonburg pinches out, onl the normal limb of the nappe is exposed at the surface (see Plate 1)

Stations 11a and 11b—Abandoned quarries in the cement limeston facies expose intermediate-type folds and drag folds overturned t the north (see Plate 10). The attitude of these folds corresponds t that of the proposed recumbent syncline below the Northampto nappe (see cross section D-D′).

Station 12—A coring program in the isolated outlier of Beekman town north and west of Egypt was recently completed by the Ne Jersey Zinc Company. Approximate positions of these drill holes ar marked by red circles on Plate 1. Every hole collared in the Beekman town encountered the Jacksonburg Formation underlying th dolomite. The maximum depth to the Jacksonburg was approximatel 450 feet. The depth to Jacksonburg decreased proportionally in hole nearer to the exposed Beekmantown-Jacksonburg contact. Thi appears to indicate a dish-shaped infold of dolomite.

Examination of the core taken from the hole marked x yield further evidence that the cement limestone facies overlies the cemen rock facies in an overturned sequence. This evidence includes th existence of: 1) black argillaceous limestone underlying dark-gra bedded limestone, and 2) inverted graded bedding.

Station 13—Recumbent similar folds and the Beekmantown Jacksonburg contact are well exposed just south of the Giant cemen plant at Egypt (Fig. 12). These folds, interpreted as digitation related to the Northampton nappe, cascade northward under th Beekmantown.

Stations 14a—Lehigh Portland quarry at Ormrod
14b—Lehigh Stone Company quarry, Ormrod
14c—Small abandoned quarry 1 mile north of Ruchsvill

At each of these localities, the Beekmantown overlies the Jacksonburg The contact dips from 5° to 30° south or southwest.

Station 15—In the Lehigh Stone Company quarry and an abandoned quarry 300 feet to the northeast, intense deformation in th Beekmantown resembles that at Station 10 in Northampton County Small-scale recumbent folds (Fig. 13) and pinch folds (Fig. 14) ar characteristic fold types. Exposures in the quarry show the deformation to be localized near the Jacksonburg contact.

Cross section D-D′ shows the nappe as it appears in a generall north-south traverse about 1 mile west of the Lehigh River. Severa interesting developments have occurred in the interval between cros section C-C′ and cross section D-D′. The infold south of the Jacksonburg outcrop belt exposes more section before being faulted out. Th Martinsburg is exposed at the surface in the trough of a small inverted

Figure 12. Recumbent similar folds in the argillaceous limestone. Folds related to this structure appear to "cascade" under the Beekmantown to the left of the photograph. One hundred yards south of the Giant cement plant, Egypt.

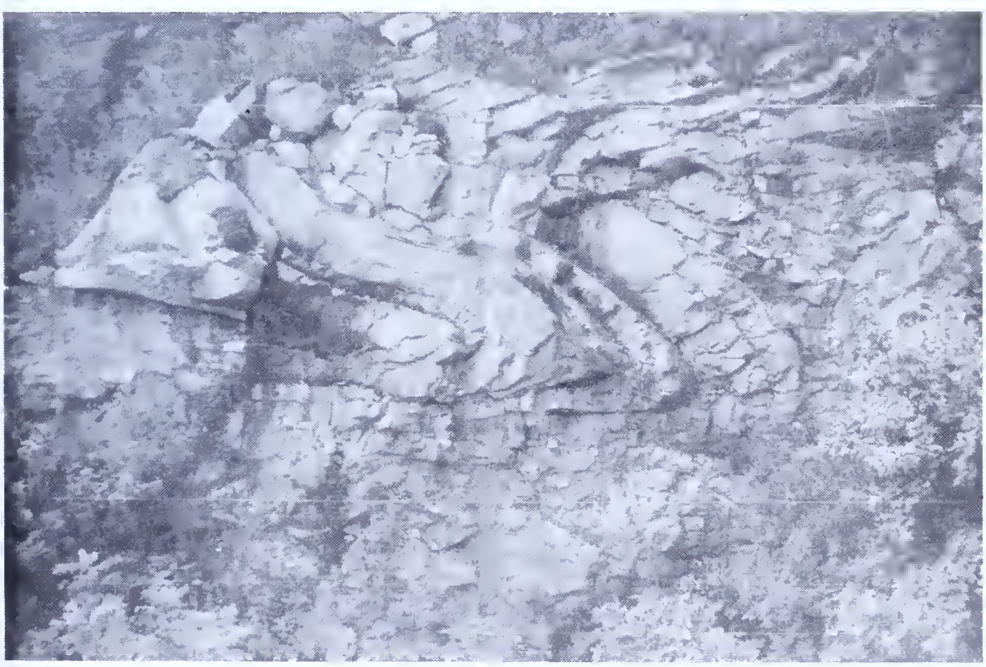


Figure 13. Recumbent folds in the Beekmantown near the Jacksonburg contact. Note the thinning in the overturned limb. Lehigh Stone Company quarry, Ormrod.

Figure 14. Complex folds in the Beekmantown dolomite. Note the fold in the lower right where voids formed in the fold crest have allowed secondary filling in the crest. Pinch folding of the detached beds is also evident. Lehigh Stone Company quarry, Ormrod.

and faulted syncline. Perhaps the most significant development in D-D′ is the dipping of the nose of the nappe over beyond 180 degrees. This has resulted in the existence of an infold of Beekmantown north of the Jacksonburg outcrop belt. Several normal faults are believed to occur in the inverted limb of the Northampton nappe in this area. One of these is exposed in the quarry of the Coplay Cement Company. Others roughly parallel to that observed are inferred from field relations and shown in cross section D-D′.

Cross section E-E′ shows the structure of the Jacksonburg belt in a traverse one mile west of D-D′. Lack of infolding to the south has simplified this section relative to C-C′ and D-D′. As mentioned for Stations 13 through 14c, exposures along this traverse show the Jacksonburg dipping both north and south under the Beekmantown. The inferred thrust fault at the nose of the nappe is still evident but the amount of throw has decreased sharply.

The most westerly exposure of the Jacksonburg associated with the nappe is located at Station 17. The cross fault at Station 16 apparently has dropped that part of the Jacksonburg which otherwise would have

cropped out between Stations 16 and 17 below surface. As a result, the Beekmantown core of the nappe now occupies that position.

No direct evidence of nappe structures was found southwest of Station 17. The Jacksonburg is absent in the section for a distance of about 4 miles where the Beekmantown and the Martinsburg are in contact. (See Plate 1.) The Jacksonburg reappears in the Fogelsville-Kuhnsville area as an isolated patch. Southwest of Fogelsville, the Beekmantown and the Martinsburg again are in contact for a limited distance.

The absence of the Jacksonburg in these two areas could be due to a structural pinch-out or it could indicate the presence of a disconformity. Conclusive evidence for either interpretation is lacking, but the writer prefers the latter theory. The evidence indicative of non-deposition or erosion is twofold: 1) In the large areas where the Jacksonburg rocks are absent, the structure does not appear to be unusually complex. In fact, the opposite may be true. At every point where observations were made along the Beekmantown-Martinsburg contact, evidence for unusually strong deformation was lacking. 2) R. L. Miller (in B. L. Miller and others, 1941) describes an exposure of the Martinsburg slate unconformably overlying the Allentown Formation (Cambrian) at Limeport, Lehigh County. This, together with the irregular nature of the Jacksonburg outcrop belt, led R. L. Miller to postulate the presence of scattered low-lying land areas during the time Jacksonburg was being deposited. Gray (1952) has found evidence that an interval of erosion took place during the early stages of Martinsburg deposition. Erosion during this interval also may have been responsible for the removal of Jacksonburg rocks.

The Jacksonburg exposed in the vicinity of Fogelsville apparently is located some distance south of the axis of the Northampton nappe. At this locality (see section F-F′, Plate 1), Jacksonburg folds are overturned to the north but recumbency is absent. It is possible that these folds are drag folds on the normal limb of the nappe. Cross section F-F′ traverses a breached anticline where the exposed Beekmantown is surrounded by Jacksonburg. Bedding-cleavage relations and the attitude of the Beekmantown and Martinsburg contacts indicate a normal sequence for most of the area. Overturning, where present, is indicated by reversal of stratigraphic sequence and cleavage-bedding relationships.

Second Generation Folds

Large Open Folds

Open folds, some with half wave lengths on the order of 0.5 miles and extending for as much as a mile along the fold axis are superimposed on earlier folds and minor structures. The two best examples

are the synclines at Stockertown and Nazareth. Both are exposed in a series of quarries in these areas.

The Nazareth syncline as exposed in the Nazareth Cement Company quarry is a broad, open, faulted syncline. The westward plunge of the syncline and associated anticline is reflected in a sigmoidal-shaped offset in the Jacksonburg outcrop belt.

The Stockerton syncline differs from the Nazareth structure in several ways. It plunges eastward rather than westward. It occurs almost entirely within the outcrop belt of the Jacksonburg without causing notable deflection in the trend of the belt. It is smaller in areal extent than the Nazareth syncline.

Evidence for designating these open folds as second generation is twofold: An axial plane flow cleavage of the early recumbent folds has been refolded. This is illustrated in Figure 25b in which the poles of flow cleavage throughout the Stockertown syncline have been plotted in equal-area projection. The crescent-shaped concentration indicates a folded cleavage plunging eastward at an angle consistent with the plunge of the syncline. Secondly, small-scale similar folds apparently related to the flow cleavage are evident within the framework of these large folds. These similar folds are interpreted as digitations belonging to the first generation of folds which have been, in turn, refolded.

Crinkle Folds

The term "crinkle folds" is used to designate the small-scale secondary folds intimately associated with slip cleavage (see later discussion). These crinkles are superimposed homoaxially on the earlier recumbent folds, distorting both bedding and flow cleavage (Fig. 15). The folds are concentric and usually disharmonic.

The size and frequency of the plications vary through a wide range. In the Keystone quarry at Bath, wave lengths of about 2 feet and amplitudes of 1 to 8 inches are typical. West of Bath this type of fold is smaller and occurs more frequently. West of the Lehigh River the wave length is commonly less than 2 centimeters. Many crinkles have a higher amplitude to wave length ratio than the above. These are almost invariably accompanied by slip cleavage.

Crinkle folds were observed only in the cement rock facies of the Jacksonburg Formation and in the Martinsburg Formation. Few occurrences are known east of Nazareth.

FAULTS

General Remarks

Faults within the Jacksonburg Formation generally do not show large-scale displacement. In many places, S_2 (flow cleavage) planes

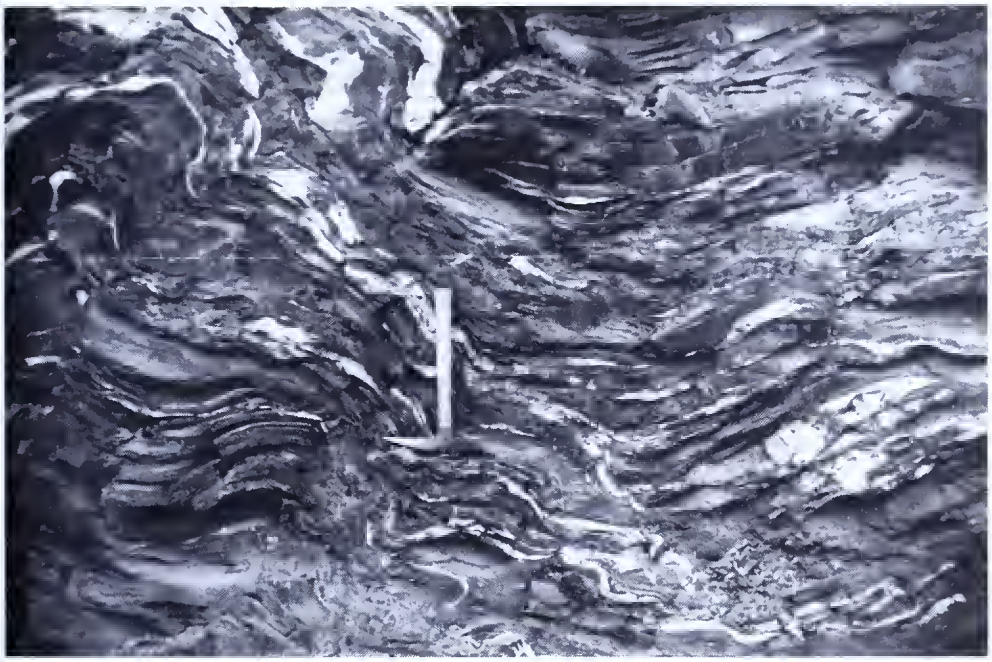


Figure 15. Argillaceous limestone showing second generation crinkle folds. Flow cleavage is the dominant S-surface in the exposure. Keystone Cement Company quarry, Bath.

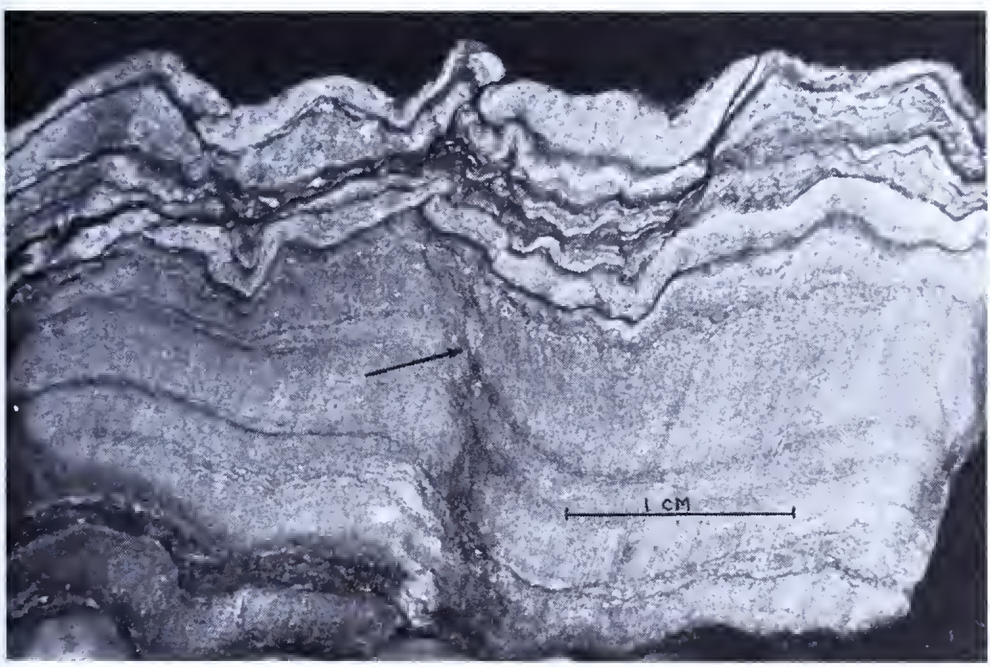


Figure 16. Close up photograph showing small scale incongruent second generation folds. Note presence of weak slip cleavage (arrow). Giant Cement Company quarry, Egypt.

have been dragged and split against fault surfaces indicating that the existence of S_2 preceded faulting. Large displacements do occur at some localities along the southern contact with the Beekmantown or Allentown.

Faults associated with the Jacksonburg belt mainly are of three types: 1) high angle thrust faults, 2) low angle thrust faults, and 3) cross faults where the type of movement is undetermined. Normal faults are rare.

High Angle Thrust Faults

These faults strike subparallel to parallel to the trend of the formation and dip steeply northwest or southeast. Those thrust faults which dip south or southeast show the greater vertical displacement.

Along the southern border of the Jacksonburg infold at Catasauqua, The Allentown Formation has been faulted into contact with the Jacksonburg. A notable divergence in bedding can be measured across the fault. This feature may be observed just north of Fairview Cemetery (Plate 1). At this point a reailroad freight yard makes a right angle approach to the Lehigh River. In the northwest quadrant defined by this intersection, outcrops of the Jacksonburg conformably overlie the Beekmantown and the entire sequence dips south. South of the tracks, along the base of the hill north of the cemetery, the Allentown dips west-southwest. Other faults of the same type are inferred from drill core data. An example of this occurs at the Jacksonburg-Beekmantown contact at the Hercules quarry at Stockertown. Drill holes just north of the contact pass through a wedge of Beekmantown in fault contact with the Jacksonburg (J. L. Dyson, oral communication).

North- or northwest-dipping thrusts are more common within the Jacksonburg belt than those dipping south or southeast. An example occurs in the abandoned Keystone quarry at Bath. The fault surface on the hanging wall dips approximately 75°NW and is exposed for a distance of nearly 2,000 feet along the stike and over 100 feet down dip. The surface undulates but maintains a position roughly perpendicular to S_2. S_2 in the footwall has been dragged upward. The magnitude of the movements is difficult to measure directly because of the homogeneity of the enclosing rock. However, two lines of evidence indicate that the dip-slip component of movement along the fault has been less than 600 feet. These are: 1) width of outcrop belt (apparent thickness of 1,050 feet vs. 900 feet extrapolated from measured sections), and 2) the presence of argillaceous limestone exposed in both the hanging wall and footwall of the fault.

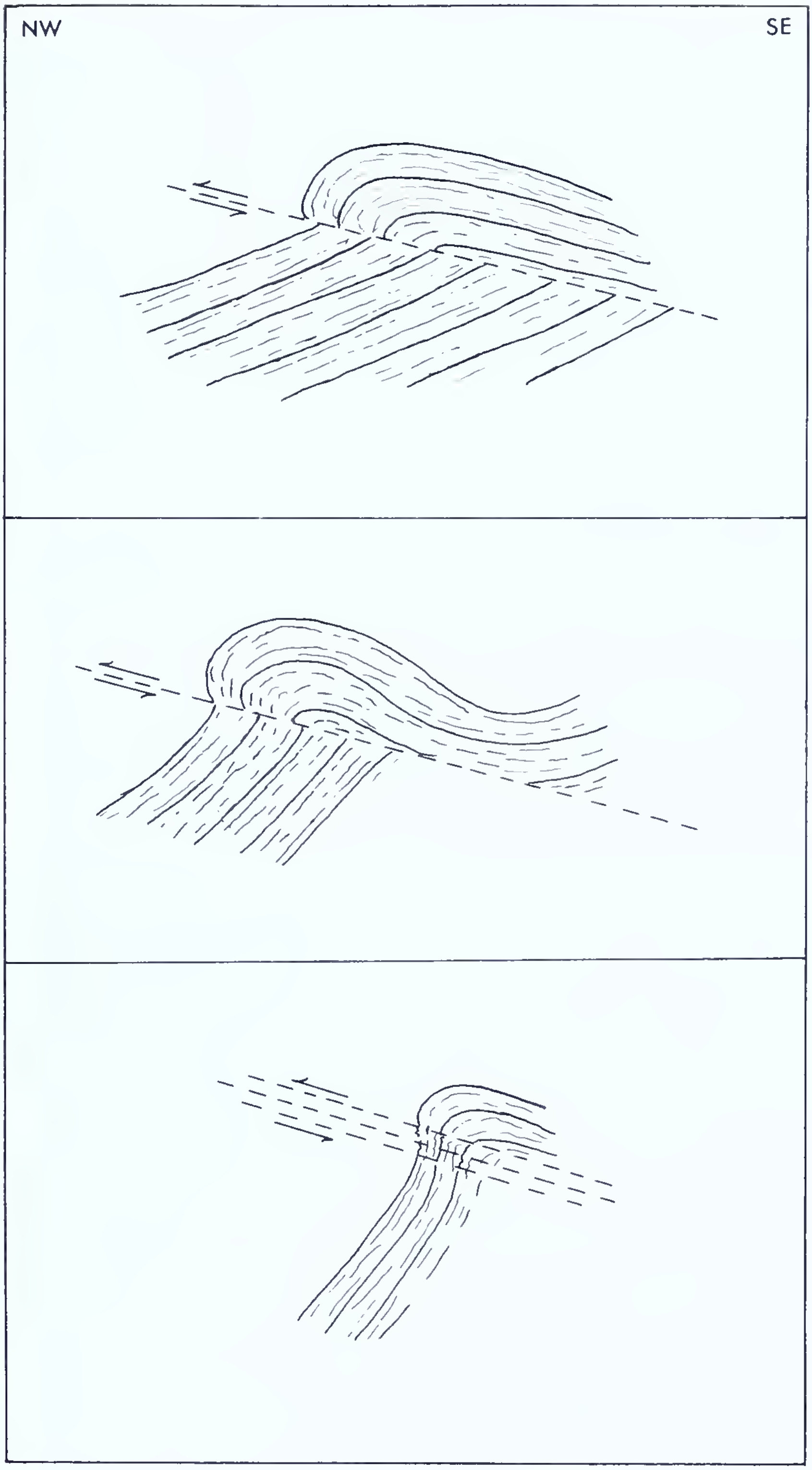


Figure 17. Three crass-sectians af a basal shear fault expased in the Lehigh Partland Cement ›mpany quarries at Sandts Eddy. Statians (fram tap ta battam) pragress fram nartheast ta sauthwest.

Low Angle Thrust Faults

A recumbent fold and associated basal shear fault are exposed in the southeast walls of the Alpha quarry No. 1 at Martins Creek. The lower crystalline limestone has been folded and thrust over the straitigraphically younger beds of argillaceous limestone. This has created an anomalous outcrop pattern in the quarry with the lower crystalline limestone exposed further northwest than would be expected.

A small basal shear fault crops out in three exposures oriented perpendicular to the strike in quarries belonging to the Lehigh Portland Cement Company at Sandts Eddy (Fig. 17). The fault shows maximum offset in the northeast exposure and dies out to the southwest. Scattered small or digitation folds in the area also exhibit basal shear (fig. 18).

The extent of basal sheer faulting in the Jacksonburg is difficult to estimate. Due to obliteration of bedding by subsequent S-planes and the homogeneity of much of the formation, positive identification of this fault type is difficult where the entire structure is not exposed.

Cross Faults

Few cross faults are actually exposed; the presence of most are indicated only by offsets of contacts or key beds. An excellent example of a cross fault mapped on this basis is located one and one-half mile

Figure 18. Minor recumbent fold with bosol sheor foult in the overturned limb. Down dip directio (northwest is to the left). Lehigh Portland Cement Company quarry, Sandts Eddy.

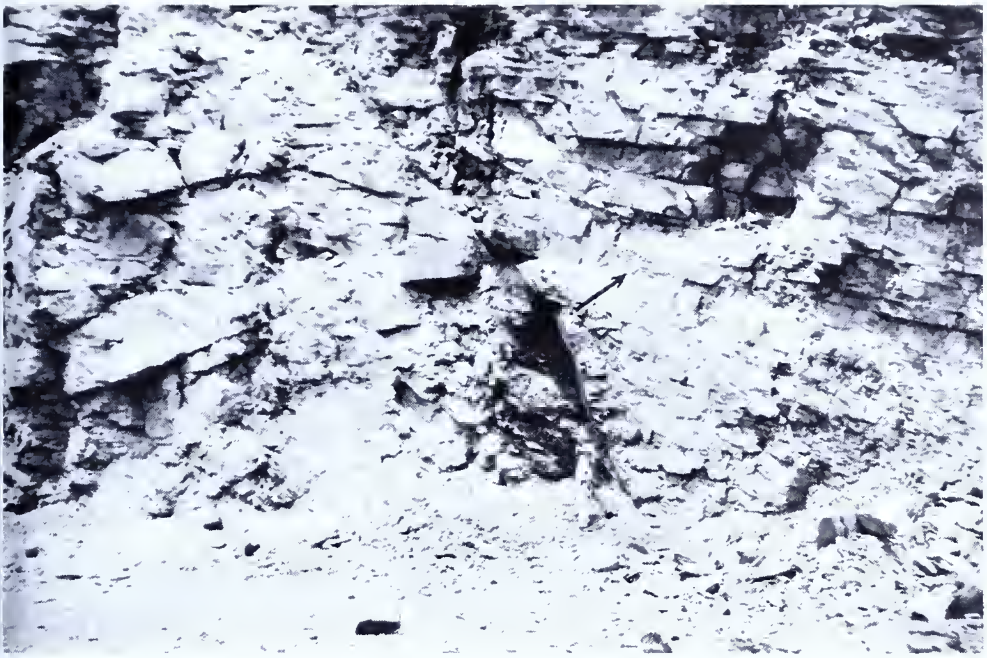


Figure 19. Cross fault exposed in the cement limestone facies. Beds on the right have moved up elative to those on the left. Note the bentonite bed (arrow) to right of fault. Nazareth Cement ompany quarry, Nazareth.

ast of Martins Creek (Plate 1). The Beekmantown Group and the Jacksonbourg Formation are in fault contact for some 1,800 feet. The fault line forms an angle at 65 degrees with the trend of the formations.

Fortunately, one cross fault is clearly exposed in the Nazareth Cement Company quarry at Nazareth. This fault is a high-angle hrust striking four degrees west of north and dipping 71°E. Dip-slip novement in the fault plane is estimated at 110 feet. The pyritic pentonite bed described earlier has been offset. The results of drilling how that the Beekmantown contact, in the trough of the syncline, as been brought up near the surface east of the fault. The nose and ateral contacts of the syncline (in the upthrow side) have migrated nward or down dip.

Normal Faults

Only one normal fault could be positively identified in the field. This structure was observed in the cut made for the haulage road of he operating quarry of the Coplay Cement Company. The fault trikes N 17°E and dips 34° NW. Platy fragments formed by S_2 have been dragged into and against the fault plane. Cement-rock lithologies exposed on either side of the fault show differing intensities of S_2 development (S_2 more intense in hanging wall). Bedding traces, lthough very obscure, appear to diverage across the fault plane.

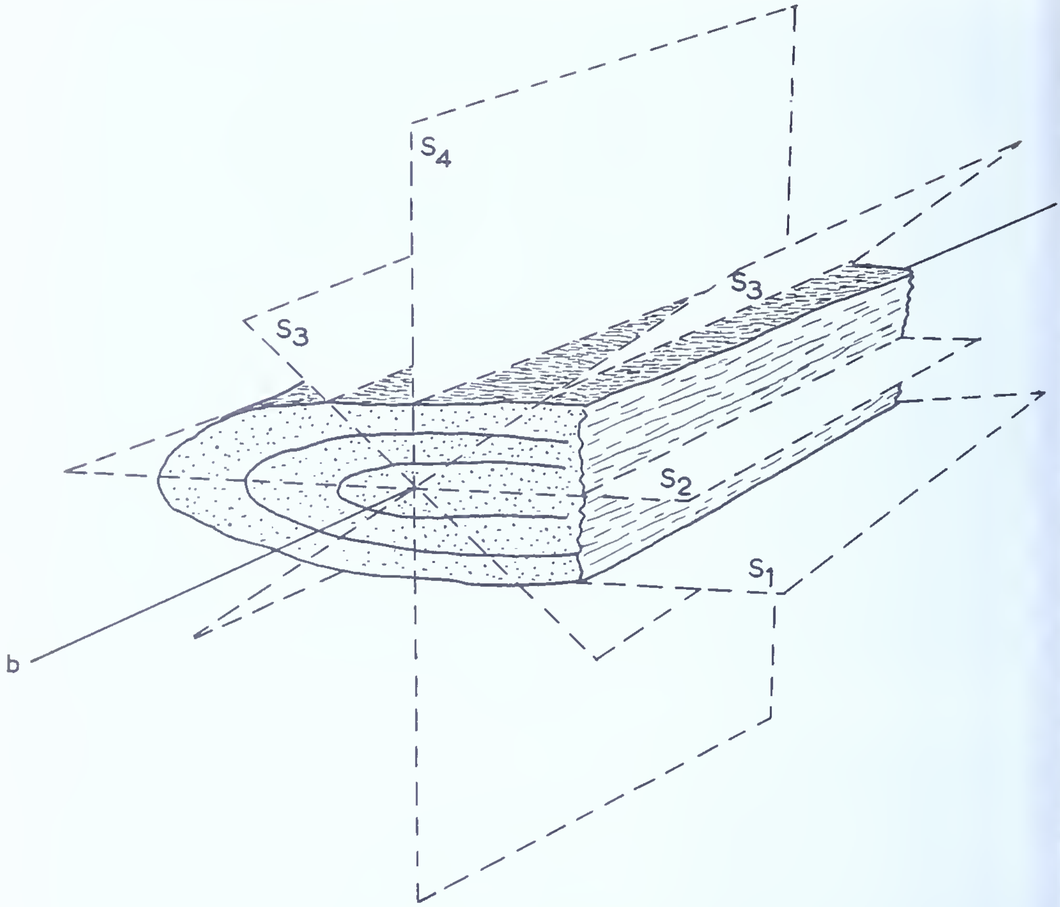


Figure 20. S-plane designation used in this report.

Other normal faults believed to be present are located 1) along the Beekmantown-Martinsburg contact striking northeast from Egypt and 2) along the north contact of the small band of Martinsburg cropping out south of the active quarry of the Giant Cement Company quarry (see Plate 1, cross section D-D′). These normal faults, both observed and postulated, occur in the area mapped as the overturned limb of the Northampton nappe.

MINOR STRUCTURES

Planar Structures

The S-plane notation of Sander (1930) for planar elements in deformed rocks has experienced widespread use in recent years. The various planes generally are classified according to age and appropriate subscript numbers are assigned to each. Planar structures in the Jacksonburg include: 1) stratification or bedding (S_1), 2) flow cleavage (S_2) throught to be genetically associated with an early phase of recumbent folding, 3) fracture or slip cleavage (S_3

ıought to be genetically associated with a second generation of folds, nd 4) a steeply dipping to vertical joint set (S_4) striking parallel to ıe general structural trend. These elements and their geometric elationships to the regional fold pattern are shown schematically ı Figure 20.

Bedding (S_1)

Bedding or S_1 is the dominant surface in most of the cement lime-;one facies and in the crystalline limestones of the cement rock ıcies. In these units the bedding surfaces may be planar but more ften they show undulations 10 centimeters or longer in wave length. 'igure 3 shows an excellent example of this feature in the quarry of ıe Nazareth Cement Company. This type of bedding has been more ıoroughly described in an earlier section on the lithology of the ement limestone.

Recognition of bedding becomes progressively more difficult to-'ard the upper part of the formation. In the argillaceous limestone f the cement rock facies bedding is obscure. It may be detected in 'esh exposures but is rarely identified in badly weathered outcrops. Vhere visible, it usually occurs as fine anastomosing seams showing ight variations of color and texture. In places, bedding is marked nly by fine crystals of pyrite. These frequently yield a brown stain n weathering. S_1 in Figure 21 represents a typical example of bedding

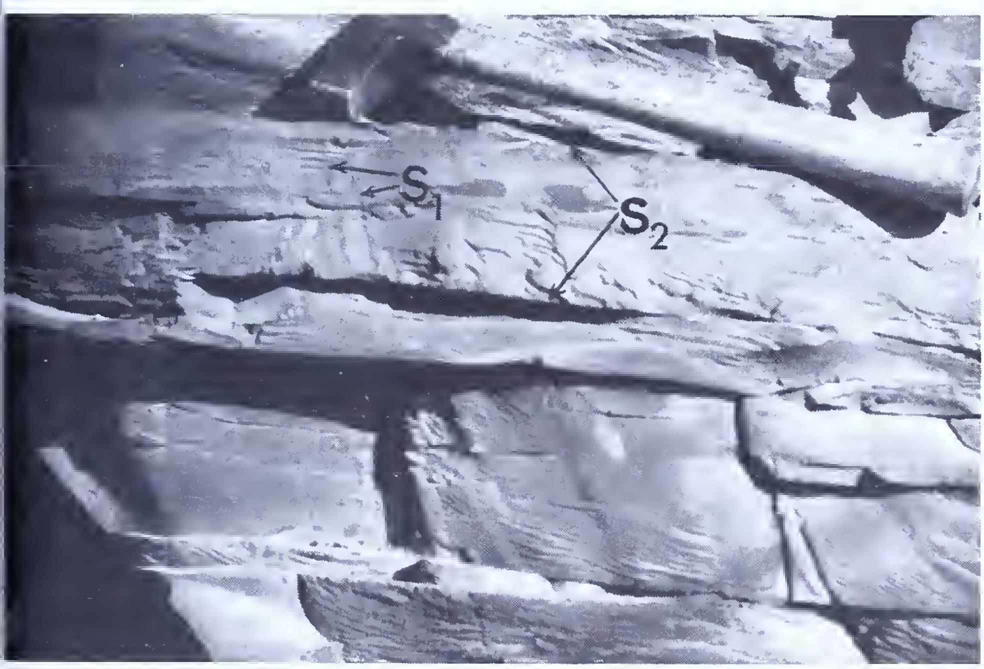


Figure 21. Argilloceous limestone showing bedding and flow cleavage. Flow cleovage (S_2) is the lominont S-plone. Bedding (S_1) intersects S_2 at a high angle and is unusually clear in this outcrop. 'oad cut 1 mile northwest of Sondts Eddy.

in the argillaceous limestone. The clarity of this bedding trace is du largely to the high angle between S_1 and S_2. Throughout most of th argillaceous limestone observed, S_1 and S_2 are nearly parallel, makin bedding difficult to detect.

Flow Cleavage (S_2)

Definition.—Flow cleavage in this paper is used essentially a originally defined by Leith (1923, p. 113):

> Flow cleavage is a structure commonly resulting from the flowage of har rocks. It is a capacity to part along parallel surfaces determined by the paralle arrangement of the longer axes of unequidimensional mineral particles and b the parallel arrangement of mineral cleavage in certain of the unit mineral parti les. Flow cleavage is characterized by platy and columnar minerals of com paratively few kinds which are well adapted to conditions of rock flowage . . Other names for flow cleavage are schistosity and slaty cleavage.

S_2 in Cement Limestone.—The cement limestone facies shows less intense development of S_2 than the overlying argillaceous lime stone. In outcrop, S_2 planes in the cement limestone may be widel spaced yielding thick slabs or angular blocks. Refraction of the S indicative of a variation in competency between beds or within single bed may be pronounced (Fig. 22).

Thin-section studies of the cement limestone suggest intense in ternal deformation. Deformation by distortion is dominant but man

Figure 22. Flow cleavage in the cement limestone facies. Note the refraction of S_2 in the interva between bedding planes. Small abandoned quarry 1 mile southwest of Coplay.

›ssils and intraclasts appear to be rotated or crushed. Constituent ırticles are elongate parallel to the S_2 direction, imparting an obvious irectional fabric to the rock. Concentrations of insoluble material so occur along S_2 planes. Figure 4 illustrates many of these features.

As is the case with the majority of minor structures discussed in ıis study, S_2 in the cement limestone facies increases in intensity › the west. S_2 is generally lacking in specimens from Jacksonburg ıd Woods Farm near Franklin, New Jersey.

S_2 in Argillaceous Limestone.—Flow cleavage attains its maximum ɜvelopment in the Jacksonburg in the argillaceous limestone of the ›ment rock facies. Primary features are virtually obliterated. :rongly oriented laminae (from 100 microns to over 1 millimeter ıick), steaks and lenticules parallel the S_2 direction. The laminae ›present partial segregation of the darker insoluble and lighter ırbonate fractions. Streaks (discussed further under *Lineation*) and nticules are composed of crushed and drawn-out calcite and fibrous ıartz pods of questionable origin.

Thin black layers of opaque material are concentrated on some S_2 ırfaces. In such cases, S_2 surfaces of freshly cleaved rock have a ıiny luster and resemble black patent leather. These concentrations ɔparently are residual and may be related to selective removal of aCO_3 along the S_2 planes. Evidence for the selective removal of ırbonate along these surfaces is twofold. First, incomplete fossils ıd calcite veins often end abruptly against the surfaces as if par- ally removed (Fig. 23). The undulating and anastomosing nature ; many of the surfaces suggest that lateral movement in the plane and ›nsequent removal of the missing fossil or vein material to another art of the rock is not likely. Secondly, notable concentrations of ısoluble material occur on these cleavage surfaces. In an effort to ɜtermine roughly the percentage of insoluble material concentrated ı two of these surfaces, about one-half millimeter of the opaque ıaterial was scraped from each of the two surfaces and treated with ilute HCl. The insoluble residues from the two samples measured 3.4 and 71.1 per cent, or roughly twice the 34.8 percent measured ›r the whole rock.

S_2 in Crystalline Limestones.—Generally, flow cleavage is difficult › identify in the crystalline limestone beds but is readily apparent ı the intercalated argillaceous limestone layers. In zones where the ›quence has undergone gentle folding, and in the limbs of isoclinal ›lds, S_2 is absent or occurs as subtle laminae in the crystalline beds. ı the crests of tight folds, the laminae can be more easily recognized. arting along the S_2 planes is not as marked as that noted in other nits of the Jacksonburg.

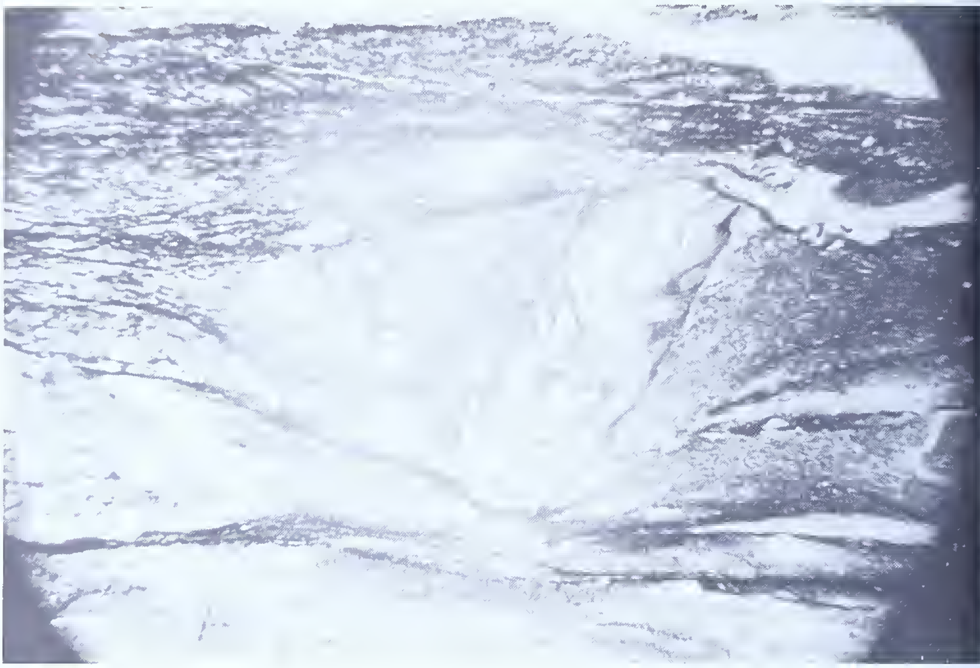


Figure 23. Photomicrograph showing branching bryozoa ending abruptly against S_2 surface. Note the concentration of opaque material parallel to S_2 and the irregular nature of S_2 surfaces. X2

A weak directional fabric consisting of distorted grains and dar parallel planes can be recognized in thin section. The pattern i similar to that in the cement limestone but is less intense.

Relation to Folds.—S_2 is oriented parallel to the axial planes of th major folds, most of which are recumbent and isoclinal. Consequentl bedding and flow cleavage are generally parallel to subparallel alon the limbs of the folds. In the crests of the folds (Fig. 24), S_1 and S intersect at high angles.

The consistently low dips of S_2 are illustrated in Figure 25. Ave ages computed on dip readings from limited areas as well as for th total area mapped fall between 20 and 24 degrees. Figure 25 als illustrates the slightly higher concentration of S_2 surfaces dippin south or southeast as opposed to those dipping north or northwes Some small variation in the strike of S_2 is noted from one locality t another (Fig. 25). This variation may be correlated with changes i trend of the major folds of the area. For example, the sample plotte in Figure 25d was taken in an area where the folds stike approx mately east-west. Figure 25c contains cleavage reading from fold striking approximately N 50°E.

Evidence suggesting a later deformation of S_2 has been previousl described. For example, at Stockertown, S_2 along with the beddin and small recumbent folds, appears to have been folded into a larg

Figure 24. Similar folds in the cement limestone facies with flow cleavage parallel to the axial lane. Note the thickening in the crest at the lower left.

pen, eastward plunging syncline. S_2 also wraps around the crinkle olds which are described in a previous section as second generation olds.

Slip Cleavage (S_3)

Description.—The distinction between slip cleavage and fracture leavage is based on the presence or absence of movement along ndividual cleavage planes (Billings, 1956, p. 359). That which shows vidence of movement is designated slip cleavage. Both slip and fracure cleavage differ significantly from flow cleavage in that there is . measurable distance separating individual slip cleavage or fracture leavage planes. Slip cleavage and fracture cleavage may be indeendent of perferred orientations of the mineral grains.

Slip cleavage in the Jacksonburg is intimately associated with a eneration of small asymmetrical folds, crinkles and crenulations uperimposed on pre-existing S_1 and S_2. These folds are usually symmetrical (fig. 15) and may have a large value for the ratio of mplitude over wave length. S_3 occurs along the attenuated limbs of hese folds. The term "slip cleavage" is deemed appropriate for this eature because of the offsets of pre-existing S_1 and S_2 indicated along he majority of the S_3 planes observed. Figures 26, 27 and 28 show lose ups of three typical examples of S_3 in the Jacksonburg. Figure 29 hows S_3 in the field. Attenuation of the fold crests or formation of uswichungsclivage was not noted in the Jacksonburg.

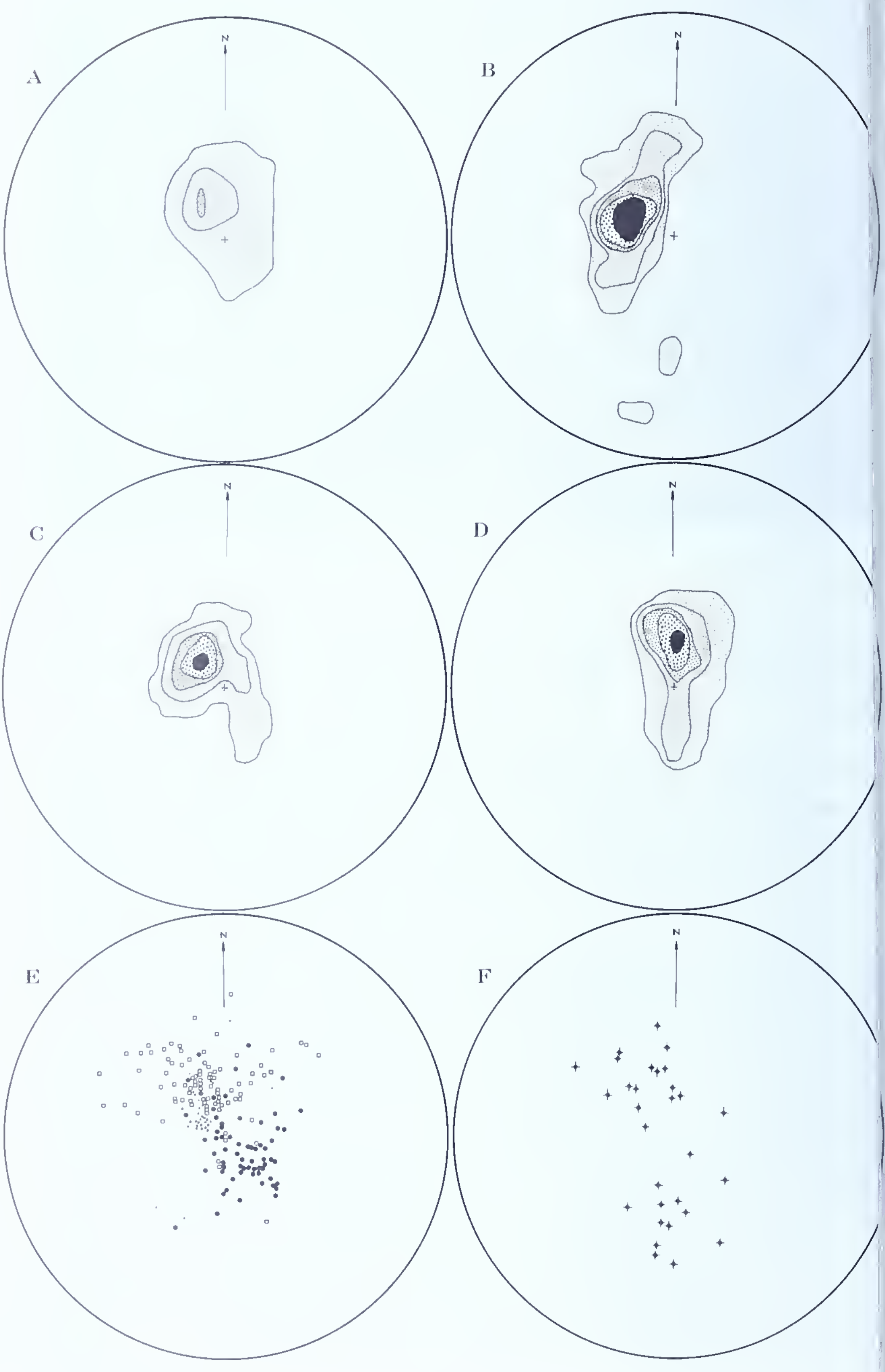

A
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Figure 25f shows poles of S_3 measured in the Jacksonburg. At any given outcrop the S_3 planes dip either to the northwest or to the southeast at angles below 45 degrees. The strike direction of S_3 appears to conform closely to that for S_2 suggesting a homoaxial relationship.

Areal and Lithologic Relations.—Slip cleavage is far less ubiquitous than flow cleavage throughout the area studied. Occurrences of slip cleavage increase in frequency westward, reaching a maximum at Fogelsville. No S_3 was observed in exposures of the Jacksonburg in New Jersey and only an incipient development, in the form of rare crenulations on S_2, was found east of Nazareth, Pennsylvania.

The eastermost occurrence of S_3 recognized in outcrop was observed in the Keystone Cement Company quarry at Bath (Fig. 26). Westward, excellent exposures showing S_3 occur along Hokendauqua Creek one mile north of Northampton and along the entrance to the operating quarry of the Dragon Cement Company (Fig. 29). In the Giant Cement Company quarry, one-half mile southeast of Egypt, S_3 is present in the north wall of the opening (Fig. 16) and absent in the south wall. The most marked occurrence of S_3 in the area mapped was observed in the Lehigh Portland Cement Company quarry at Fogelsville (Fig. 27).

A clear relationship exists between the degree of S_3 development and rock type. Slip cleavage was not found in the cement limestone facies. It is most prominent in sequences of thinly interbedded competent and incompetent rocks. The S_3 may be present in either type of bed. At Bath, the S_3 is associated with the argillaceous strata in and near the lower crystalline limestone. At Fogelsville where S_3 is common throughout the cement rock facies, the planes are particularly numerous in thin layers and lenses where grain size exceeds that in contiguous beds.

Figure 25. Diagrams of Poles of Slip and Flow Cleavage (lower hemisphere projection on Schmidt or equal area net; contours represent 4-8-12-16-20%).

a. Contour diagram of poles of all S_2 measured in the Jacksonburg Formation. 1,090 points plotted.

b. Contour diagram of poles of S_2 from the Stockertown syncline. Note the crescent-shaped concentration and its relation to the eastward plunge of the enclosing syncline. 49 points plotted.

c. Contour diagram of poles of S_2 from the Lehigh River to Egypt. Note the relationship between the point concentration and the local trend of the formation (approximately N50° E).

d. Contour diagram of poles of S_2 measured in the Weaversville-Northampton area. The east-west strike of the formation and the low regional plunge of folds is reflected in the cleavage pattern. 163 points plotted.

e. Poles of S_2 measured in the Martins Creek-Sandts Eddy area.

- ◻ Poles of S_2 measured in the cement limestone facies.
- • Poles of S_2 measured in the argillaceous limestone of the cement rock facies.
- ● Poles of S_2 measured in the argillaceous interbeds in the crystalline limestones of the cement rock facies. The regional strike in this area is N60° E.

f. Poles of slip cleavage measured throughout the area mapped.

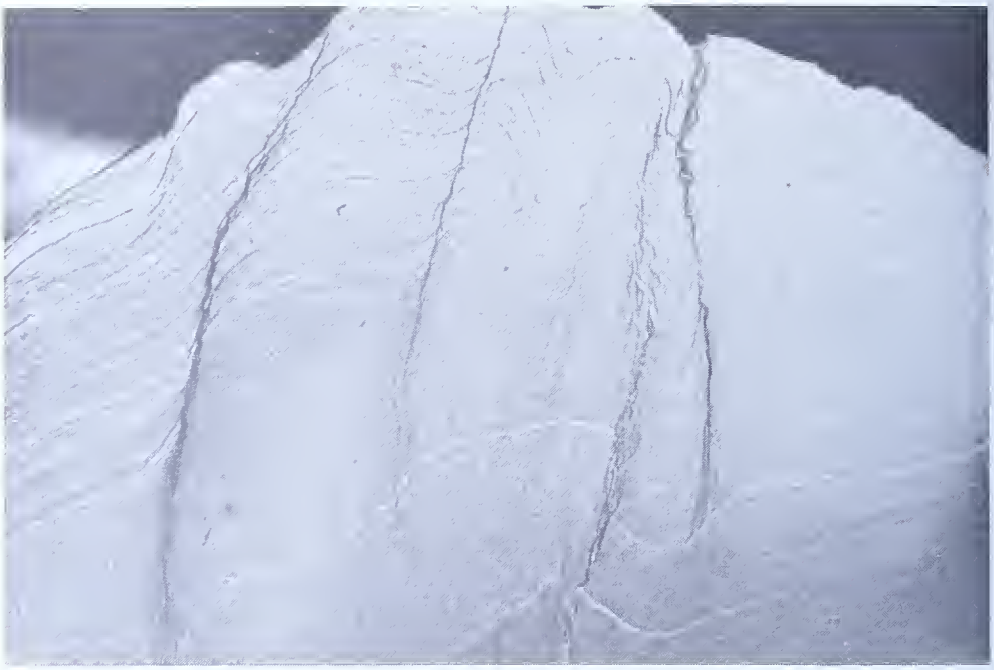

Figure 26. Photograph of a polished section showing slip cleavage (S_3) in the argilloceous limestone. Flow cleavage (S_2) has been folded into high omplitude folds. Note the position of S_3 in the fold limbs. Specimen from Keystone Cement Company quarry, Both. X2.

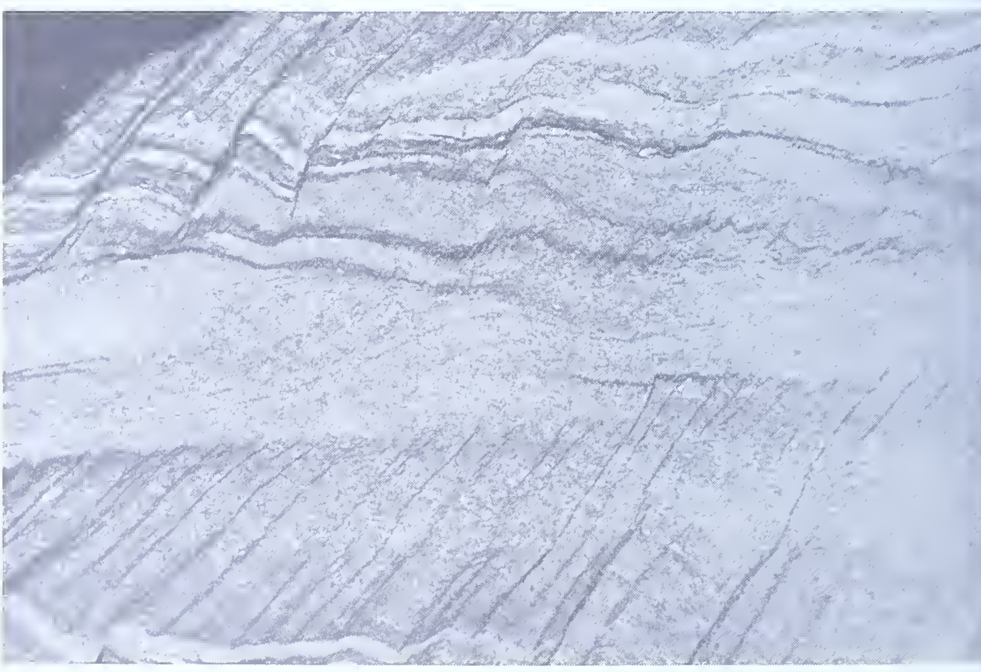

Figure 27. Photograph of a polished section showing closely spaced slip cleovage. These structures are developed in a thin, relatively competent bed of calcarenite. Specimen from Lehigh Portland Cement Company quorry, Fogelsville. X4.

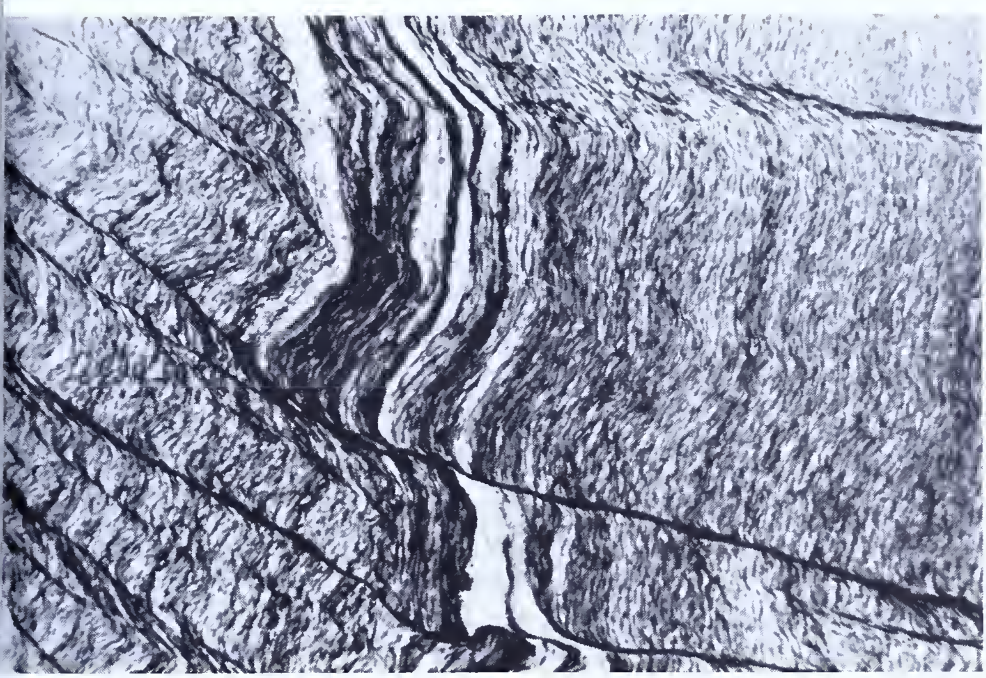

Figure 28. Phatamicragraph shawing folding af flow cleavage (S_2) with related slip cleavage (S_3). Marked mavement has accurred along the strong S_3 surface in the center af the phatagraph. X7.

Figure 29. Flow cleavage (S_2) and slip cleavage (S_3) in autcrap. S_2 has been strangly falded and dips steeply ta the right af the phatagraph. S_3 has farmed in the fald limbs and dips gently ta the left. Dragan Cement Campany quarry, Narthamptan.

The apparent correlation between S_3 planes and alternating lithology in the Jacksonburg appears analogous to a situation described by Choquette (1960) in working with the Cockeysbille Marble of Maryland. Choquette explained the lack of slip cleavage in the Cockeysville as due to the homogeneous and relatively plastic nature of the formation. He theorized that during deformation the rock could not transmit stress. Consequently, during prolonged or repeated deformation, later stresses were dissipated along pre-existent flowage planes. The related Wissahickon, where variations in lithology are marked, shows both flow and fracture (or slip) cleavage.

Joints

General Description.—Virtually every outcrop observed during the course of the present study was cut by joints. Most of the joints are planar and smooth. Slickensides are rare. Calcite and quartz deposits are common on joint planes near the ground surface. Exposures in quarry walls show that these deposits diminish with depth. This may indicate a relatively recent age for the quartz and calcite.

The size and spacing of the joints appear to be related to the lithology and structure of the rocks in which they occur. The largest joint surfaces (often hundreds of square feet in area) were observed in sequences of homogeneous rock such as the argillaceous limestone of the cement rock facies and the thick-bedded parts of the cement limestone facies.

Spacing of joints varies from several feet to less than an inch. The close spacing occurs: 1) where beds are tightly folded, and 2) in parts of the formation made up of thin beds of different competency.

Orientation.—Joints throughout the area studied characteristically show steep dips. Computation of the arithmetic mean of the dip angle (regardless of direction) for all joints measured yields the figure 74.02 degrees. This steepness of dip holds regardless of rock type or structure. (See contoured diagrams, Fig. 30).

The dominant joint set in the area mapped is that earlier designated as S_4. This set follows a northeast-southwest trend and dominates

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Figure 30. Contour Diagroms of Poles of Joints (lower hemisphere projection on Schmidt or equol area net; contours represent 2–4–6–8–10%).

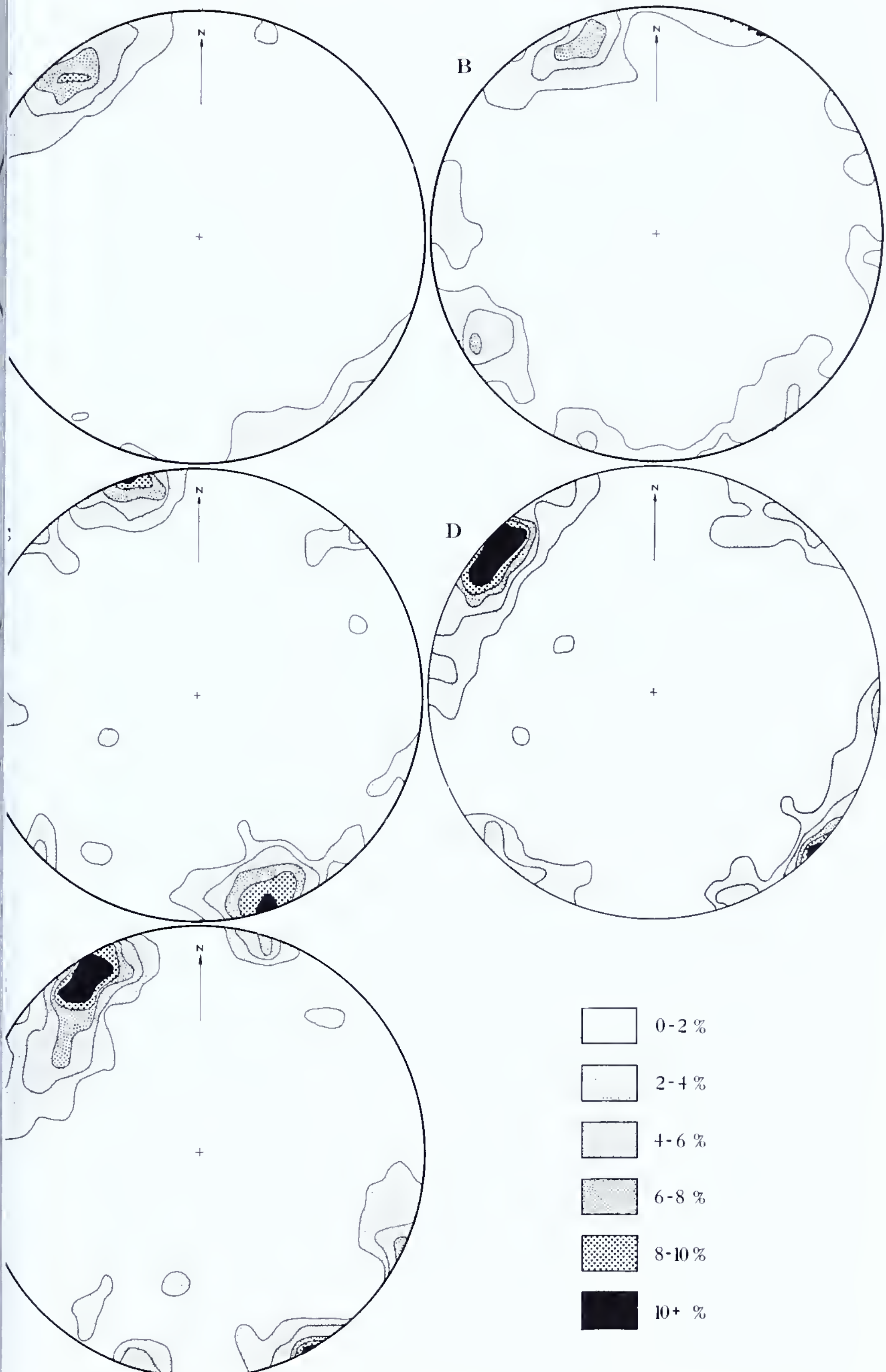
a. Contour diogrom of poles of oll joints meosured in the Jocksonburg Formotion. 1,093 points plotted.

b. Contour diogrom of poles of joints meosured in the Beekmantown group. 253 points plotted. Note the concentrotion in the southwest quodront representing cross (or ac) joints.

c. Contour diogrom of poles of joints meosured in rood cut at Block Hill, 1 mile northwest of Sondts Eddy. 140 points plotted.

d. Contour diogrom of poles of joints meosured in the Keystone Cement Compony quorry, Bath. 160 points plotted.

e. Contour diogrom of poles of joints meosured in the Giont Cement Compony quorry at Egypt. 150 points plotted.


N
B
N
N
D
N
N
0-2 %
2-4 %
4-6 %
6-8 %
8-10 %
10+ %

regardless of local variations in lithology or structure. Figure 30 (Diagrams c, d and e) shows the similarity in orientation of joints measured in three widely scattered localities in the Jacksonburg. The differences in lithology, structure and regional trend of each of these localities can be seen, in turn, in Table 3. Strong concentrations of points representing S_4 also occur in Diagrams a and b of Figure 30.

Aside from S_4, the only other joint set which can be recognized consistently in the area mapped is the relatively weak set of cross joints or *ac* joints. Cross joints generally are thought to be tension joints (Hills, 1939, p. 145; DeSitter, 1959, p. 132) caused by stretching in the crest of folds causing fracture perpendicular to the fold axis. Cross joints in the mapped area are most numerous in the competent Beekmantown dolomites and least numerous in the relatively incompetent argillaceous limestone.

Linear Structures

General Description.—Lineations observed in the Jacksonburg are of two types, those parallel to the *b* or fold axis direction and those perpendicular to *b* and subparallel or parallel to *a*. Lineations parallel to *b* include: 1) intersections of bedding and cleavage, 2) intersections of cleavages, 3) axes of drag folds, 4) boudinage, mullion and rodding, and 5) pyrite grain elongation. Slickensides and mineral streaking occur in the *a* direction on S_1 and S_2 surfaces. The plunge of slickensides and mineral streaks may vary considerably in the *ac* plane due to second generation folding of S_1 and S_2.

Intersections of Bedding and Cleavage.—In virtually all cases lineation formed by the intersection of bedding and cleavage involves S_1 and S_2. Intersections of S_1 and S_3 are rare. The lineation formed is a *b* lineation (Fig. 31).

The best examples of this kind of lineation occur in the bedded limestones of the cement limestone facies. The lineation is particularly clear in exposures where S_1 and S_2 intersect at high angles. The bedding planes of these limestones are marked by parallel grooves, cracks, or crenulations which follow the cleavage traces. In some exposures concentrations of dark scaly material on bedding surfaces mask the lineation, except where parting parallel to S_2 has taken place.

Bedding-cleavage intersections are relatively rare in many parts of the cement rock facies. This is due to the parallel or subparallel relationship between S_1 and S_2 in the limbs of isoclinal folds. Since S_2 is the dominant S-plane in the argillaceous limestone of the cement rock facies, this form of lineation is generally observed as traces of bedding on flow cleavage surfaces. The trace of bedding consists of bands defined by differences in color and texture or by thin seams of pyrite.

Table 3. *Lithology and structure of locations where joints were measured (Fig. 25, diagrams C, D, and E).*

Area	*Lithology*	*Folding*	*Cleavage*	*Trend of Folds*	*Approx. Strike of S_4*
Black Hill (One mile NW Sandts Eddy)	Argillaceous Cement Rock	Small Recumbent Folds. Upper Limb Recumbent Anticline?	S_2 strong S_3 absent	N 70°E	N 44°E
Keystone Quarry, Bath	Argillaceous Cement Rock Crystalline Limestone	Homoclinal Dip or Upper Limb of large Recumbent Anticline	S_2 strong S_3 moderate	N 36°E	N 43°E
Giant Quarry Egypt	Argillaceous Cement Rock	Complex Folds and Faults	S_2 strong S_3 strong	N 60°E	N 51°E

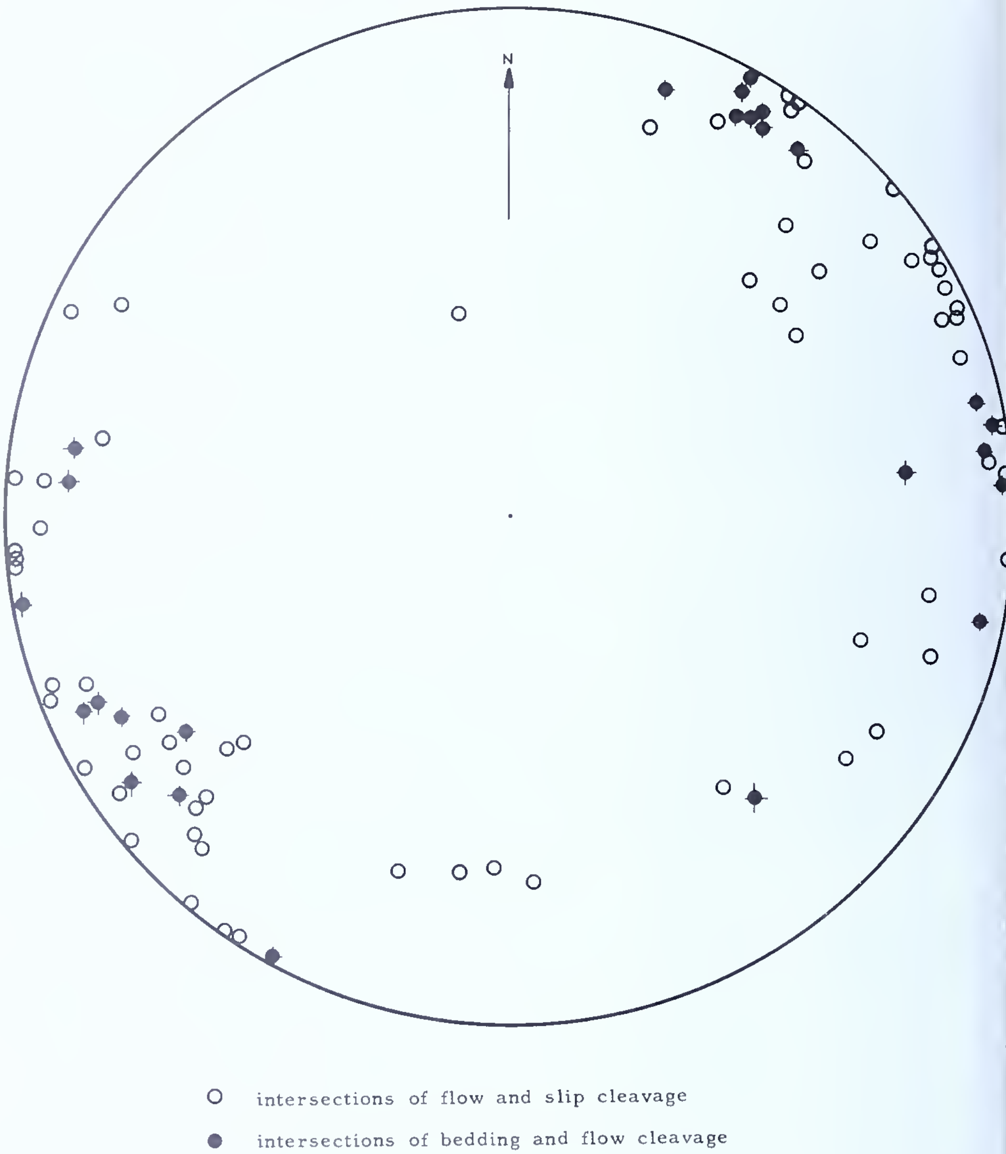


Figure 31. Diagram of two types of lineation measured in the Jacksonburg Formation. Point plotted on Schmidt or equal area net, lower hemisphere projection.

Intersections of Cleavages.—Intersections of flow cleavage and sli cleavage form a *b* lineation (Fig. 31). This is the most common linea tion observed in the Jacksonburg Formation despite the fact that i is virtually limited to the cement rock facies. Movements on the sli cleavage surfaces have produced a series of tiny en echelon fault offsetting flow cleavage surfaces. These small offsets appear on th S_2 surfaces as undulations and crinkles parallel to the *b* directio (Fig. 32). The wave lengths of these undulations or crinkles vary i magnitude from one millimeter to over five centimeters.

Figure 32. Close up photograph showing lineation produced by intersections of flow cleavage ıd slip cleavage. Giont Cement Company quorry, Egypt.

Since slip cleavage increases in intensity to the west, lineations ›rmed by cleavage intersections also become more common west- ʼard. However, in the eastern part of the mapped area (i.e. Martins ʼreek) a few weak lineations of this type were measured. This point ; east of any locations where slip cleavage could be recognized in the eld. S_3 at Martins Creek is in an incipient state and can only be lentified by use of the microscope.

Axes of Drag Folds.—True drag folds in the Jacksonburg are irtually limited to the cement limestone facies. Individual folds are mall, not exceeding five feet in cross section and bear a systematic elationship to the parent folds.

Drag fold axes measured in the Jacksonburg are parallel to sub- arallel to the regional trend of the formation. Generally, they plunge ess than 10 degrees in either a northeast or southwest direction.

*Boudinage, Mullion and Rodding.**—Boudinage is common in the rystalline limestones of the cement rock facies (Fig. 33). It occurs o a more limited extent in the cement limestone facies and in the ıterbedded dolomite and limestone sequences of the Beekmantown Group. The longitudinal axes of individual boudins are parallel or ubparallel to tectonic *b*.

*Mullion and rodding are used as described by DeSitter (1959).

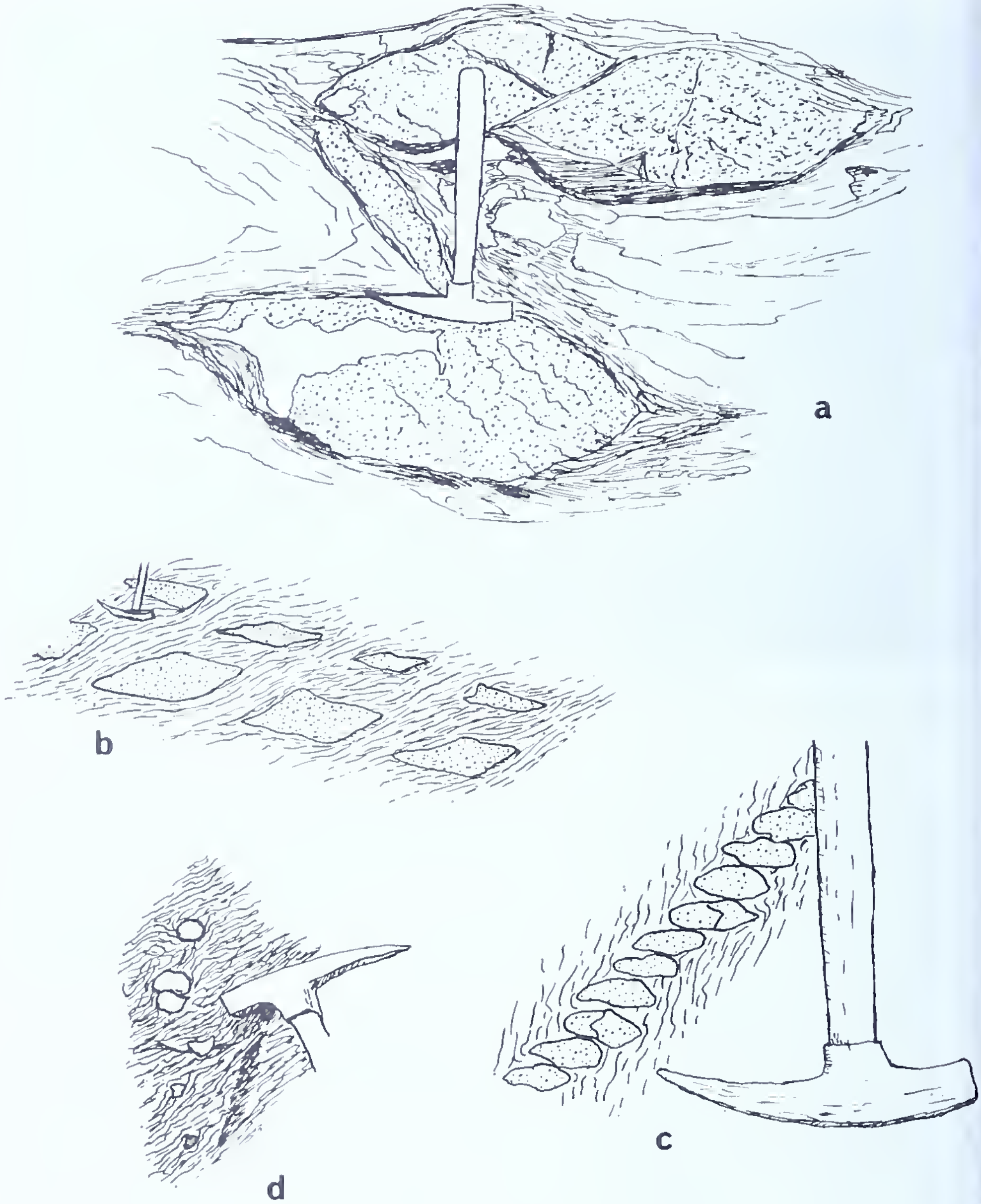


Figure 33. Boudinage, mullion and rodding in the Jacksonburg.

a. Boudinoge in deformed crystalline limestone bed. Position of the boudins indicates possibl refolding after formation (Giant quarry, Ormrad).

b. Boundinage in the cement limestone showing individual boudins completely separated. (Lehig Portland quarry, Sandts Eddy)

c. Mullion structures (?) (Abandoned quarry on 7th St. Pike, 1 mile west of Coploy)

d. Rodding invalving *Prasapara* (Nazareth quarry, Nazareth).

In the Jacksonburg Formation, adjacent boudins may be attached r completely separated. Where they are attached, the thin connecting one often contains recrystallized calcite as might be expected from Rieke's principle. Where adjacent boudins are completely separated, ach void is occupied by argillaceous limestone which apparently as flowed into the opening from adjacent beds.

In cross section, the long axis of individual boudins ranges from a ew inches to greater than 3 feet. There was no opportunity in the eld to measure the longitudinal dimension.

One exposure of an unusual linear structure in the Jacksonburg esembles DeSitter's (1959, p. 89) description of mullion structure. thin bed of crystalline limestone in an argillaceous limestone equence has been deformed into a series of oblate rods 1½ inches in iameter and elongate parallel to *b*. These are arranged in a steplike ashion. (Fig. 33c).

Rod-like structures parallel to *b* occur at several localities in the acksonburg. These are of two types: 1) irregular quartz rods, and 2) apering rods formed in conjunction with *Prasopora* colonies. The quartz rods appear to have been deposited as vein quartz which has een subsequently folded, broken and possibly rotated. They are ound in zones where deformation is intense. The tapering rods pproximately one by five inches in size and containing *Prasopora* vere found in the south limb of the Nazareth syncline (Fig. 33d). ncompetent shaly beds containing *Prasopora* are interbedded with nore resistant calcarenites. Apparently, flexural slip movement elated to the formation of the large open syncline has rotated the ndividual *Prasopora* colonies. Crystalline calcite and quartz then could be deposited in the pressure voids created in the *b* direction.

Pyrite Grain Elongation.—Large numbers of pyrite crystals were found in the pyritic bentonite bed which occurs at several localities n the area mapped. The individual pyrite crystals show a marked elongation which is parallel to tectonic *b* of the enclosing folds. Voids and pseudomorphs of fibrous quartz in the shape of the pyrite crystal also occur at one or both ends of the individual crystal in the *b* direction. This suggests a movement of the grains parallel to *b*.

Slickensides and Mineral Streaking.—Slickensides and mineral streaking in the Jacksonburg occur in the form of pyrite, calcite, and quartz streaks and striations on flow cleavage and bedding surfaces. These features curve and bifurcate in an irregular fashion but strike roughly parallel to *a* direction and perpendicular to the *b* direction. Large numbers of lineations of this type were observed in exposures where S_1 and S_2 had been refolded homoaxially into small scale crinkles and undulations. Consequently, the slickensides and mineral

streaks, oriented transverse to the folds, show a great variation in plunge within the *ac* plane.

Flow cleavage planes which contain slickensides and mineral streaking characteristically are coated with concentrations of black insoluble material described in the previous section on flow cleavage. The discontinuity in the rock fabric and the concentrations of platy mineral fragments, represented by these surface coatings, may be important factors in localizing the movements which produced slickensides and mineral streaking.

DISCUSSION

REGIONAL IMPLICATIONS OF JACKSONBURG STRUCTURE

Distribution of Similar Structures

Reports of recumbent folds in the Appalachians have become increasingly common in recent years. Recumbent folds and thrust structures are widespread in the southern Appalachians (Eardley, 1951). Recently, Ern (1960) and Goodwin (1960) have proposed the existence of a large nappe structure in the Paleozoic rocks of central Vermont.

In Pennsylvania, recumbent folds have been mapped in: 1) The Great Valley Section of the Valley and Ridge Province, 2) the Piedmont Province, and 3) the Appalachian Mountain Section of the Valley and Ridge Province (Fig. 34).

Great Valley Section

Behre (1927) described the folding in the Martinsburg of Northampton County, Pennsylvania, as largely overturned or recumbent.

Stose and Jonas (1927) published a geologic map of the Lancaster quadrangle showing many overturned dip symbols.

Gray (1952) described extensive recumbent folds in Lebanon and Berks Counties. Gray and others (1958) also published geologic maps of the Lebanon and Richland quadrangles in Berks and Lebanon Counties. This area is underlain primarily by overturned Cambro-Ordovician strata indicating the presence of nappe features. The areal extent of these structures (at least 20 miles long by 4 miles wide) is truly Alpine in scale.

Piedmont Province

Wise (in Wise and Kauffman, 1960) worked out the cross section and described in detail an instance of recumbent folding in the Beekmantown 3 miles east of Elizabethtown, Lancaster County. In

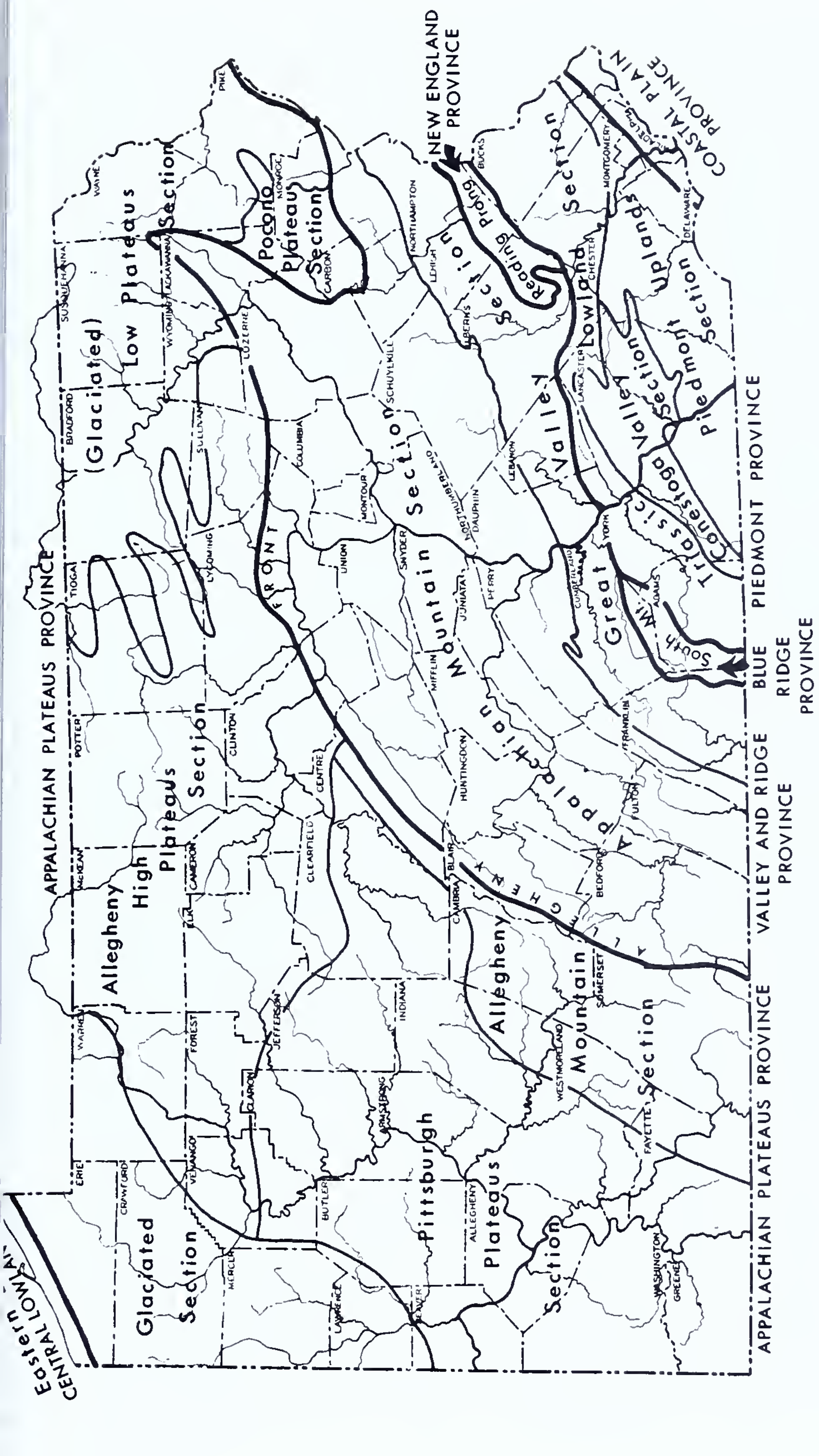


Figure 34. Map showing physical divisions of Pennsylvania.

the same work he refers to large areas of overturned strata in th Cambrian, just north of the City of Lancaster.

Bailey and Mackin (1937) described a recumbent fold in th Avondale-Doe Run area of the Pennsylvania Piedmont, southwest o Philadelphia. The structure plunges southwestward and is overturne to the northwest. Formations involved belong to the Glenarm Serie of probable Precambrian and Lower Paleozoic age.

McKinstry (1961) has completed detailed studies of the Avondale Doe Run section and surrounding areas involving the Glenarm Series He describes overturned and recumbent folds and two generation of folding. Recumbency is caused largely by warping of axial plane which originally had steeper dips.

The Appalachian Mountain Section

Dyson (1956) describes an occurrence of recumbent folding involv ing Silurian and Devonian rocks. This structure is exposed nea Palmerton, Pennsylvania, where the fold attains a magnitude o approximately 1 mile across the strike and 4 miles along the fol axis. It would appear, however, that large scale recumbent folds ar rare in this portion of the Valley and Ridge Province.

Gravity Tectonics and Appalachian Structure

Development of the Gravity Concept

The widespread occurrence and frequently large size of recumben structures in folded mountain chains has given rise to a critica evaluation of the classical theories of mountain building. Earl workers studying folded mountains, notably the Alps and Appalachians believed that the theory of lateral compression could be used to ex plain the structural features observed. Famous papers by Willi (1893) on the Appalachians and Heim (1921), Cadisch (1953) an others on the Alps, emphasized the amount of crustal shortenin necessary to produce the observed folding. For example, Heim an Cadisch suggested that the amount of crustal shortening in th Swiss Alps was on the order of 25 per cent. Jefferies (1952) dispute this figure as impossible on geophysical grounds. Many subsequen geologists also have challenged this figure.

Gravity tectonics as a basic concept and a primary cause of foldin has been comparatively late in developing. Only in the last 3 decade has the concept been expanded to a general theory and gained a measure of acceptance. One of the several noteworthy papers durin this span is that by Gignoux (1948). Gignoux utilized the data o rock flowage developed by Griggs and others to prove the limite rigidity of rocks and their tendency to flow at high temperature and confining pressures. R. W. van Bemmelen (1954), in his classica

work on mountain building, presents a bicausal theory of mountain building. The initial phase of vertical uplift is followed by a phase of dermal and epidermal denudation caused by gravity flow or gliding. In this sense, gravity would be the underlying cause of all mountain-derived folding.

Gravity Concepts Applied to Jacksonburg Structure

The author believes that recumbent folding in the Jacksonburg is best explained as a consequence of gravity gliding. This judgment is based on three lines of evidence: 1) the availability of a slope, 2) the nature of the recumbent folds in the Jacksonburg, and 3) the widespread occurrence of recumbent structures in other parts of the Appalachians.

Every known example of extensive recumbent folding occurs along the flanks of great tectonic upheavals where the down-slope environment may be conducive to gravity movement. The recumbent folds associated with the Jacksonburg belt are no exception, cropping out along the northwest flank of the Precambrian Reading Prong.

Utilizing the measured thickness of the pre-Jacksonburg Paleozoics and the difference in elevation between the crest of the Reading Prong hills and the present outcrop belt of the Jacksonburg, a rough approximation of the present-day slope of the Precambrian basement can be obtained. This was computed for the traverse from South Mountain to Northampton with the following results:

$$\frac{\text{difference in elevation}}{\text{horizontal distance}} \quad \frac{4{,}800 \text{ feet}}{39{,}500 \text{ feet}} = \text{a sine of } .1215 \text{ or } 7^\circ$$

Admittedly, it is extremely difficult to prove the existence of this slope in Paleozoic times, but in this connection three factors may be considered.

1) It is generally accepted that the true Appalachian "high" from which folding originated was located southeast of the Reading Prong. Possibly, South Mountain is an eroded stump of the northwest limb of this high.
2) Geophysical evidence presented by Hersey (1946), Socolow (1959) and Bromery (1959) suggests that no major offsets are present in the crystalline basement between the Jacksonburg outcrop belt and the Reading Prong.
3) The figure of 7 degrees is nearly twice that usually designated as sufficient for gliding in large masses. Reeves (1924) describes gliding on a 3-degree slope in the Bear Paw Mountains of Montana. Van der Fliert (in DeSitter, 1959, p. 275) proposes a 3-5 degree slope for gravity movements in Djebel Friktia, Algeria.

Digitations associated with the Northampton nappe in many places occur as cascades or "fold piles". Such cascades appear to be comparatively local features suggesting a piling-up of beds to fill a pre-existing "low".

R. W. van Bemmelen (1954), and others, have pointed out that in most folds of this large-scale recumbent type, the younger beds have "outrun" the older in the tectonic scene. That is to say, the younger beds have moved farther in the direction of overturning than the underlying older beds. This is difficult to visualize in lateral compression, where lateral movement in the basement would tend to drag the older beds, and possibly even produce asymmetry in the opposite direction. Dr. van Bemmelen (oral communication) goes on to state his belief that the deformational environment of pure lateral stress is never responsible for large-scale recumbent folding.

Finally, the incompetent nature of the Jacksonburg leads the writer to believe that it is highly unlikely that it could transmit horizontally applied stress over large horizontal distances. Gravitationally derived stresses would act directly on each individual particle of the elastico-viscous mass. Certain large scale features outside of the Jacksonburg belt also suggest deformation by gravitational gliding. The results of a recent aeromagnetic survey across the Reading Prong adjacent to the area mapped have been described by Bromery (1959, p. 16A):

> A broad positive magnetic anomaly in an area of Cambrian and Ordovician sedimentary rocks 3 miles north of Bethlehem is interpreted as caused by Precambrian rock buried at a depth of 1 mile. The exposure of Precambrian rocks at Pine Top and Camels Hump on the south side of the anomaly has little magnetic expression, but Precambrian rocks exposed 5 miles to the northeast (Chestnut Hill) have a pronounced magnetic expression.

This evidence points to an almost certain lack of "roots" for Pine Top and Camels Hump. Furthermore, it appears that the most logical explanation for the presence of these crystalline blocks located over 3 miles north of the Precambrian and resting on the Paleozoic sediments is gravity gliding.

Based on the present work in the Jacksonburg, it becomes clear that detailed studies of the structure of the Cambrian and Lower Ordovician succession in Lehigh and Northampton Counties is needed. It is felt that such studies, combined with the present work would contribute substantially to the understanding of Appalachian structure in eastern Pennsylvania.

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GEOLOGIC CROSS SECTIONS

Horizontal scale of Cross Sections twice scale of map.

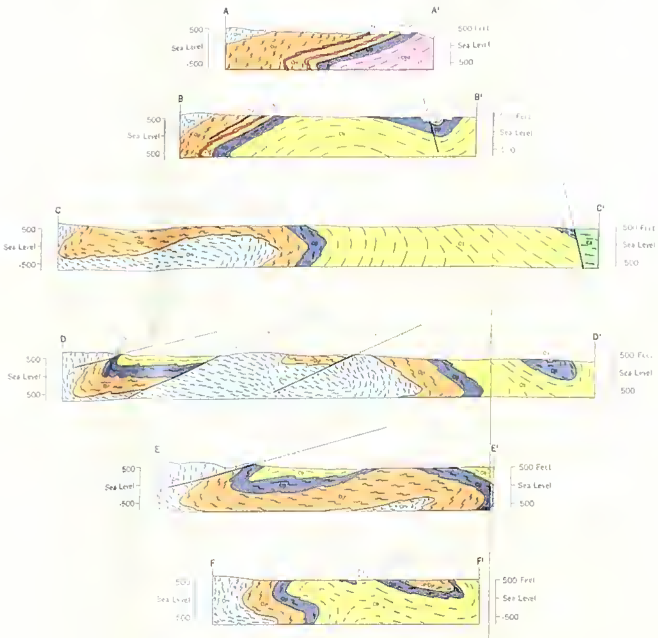

Plate 1. Geologic map of the Jacksonburg Formation in Lehigh and Northampton Counties, Pennsylvania

COMMONWEALTH OF PENNSYLVANIA
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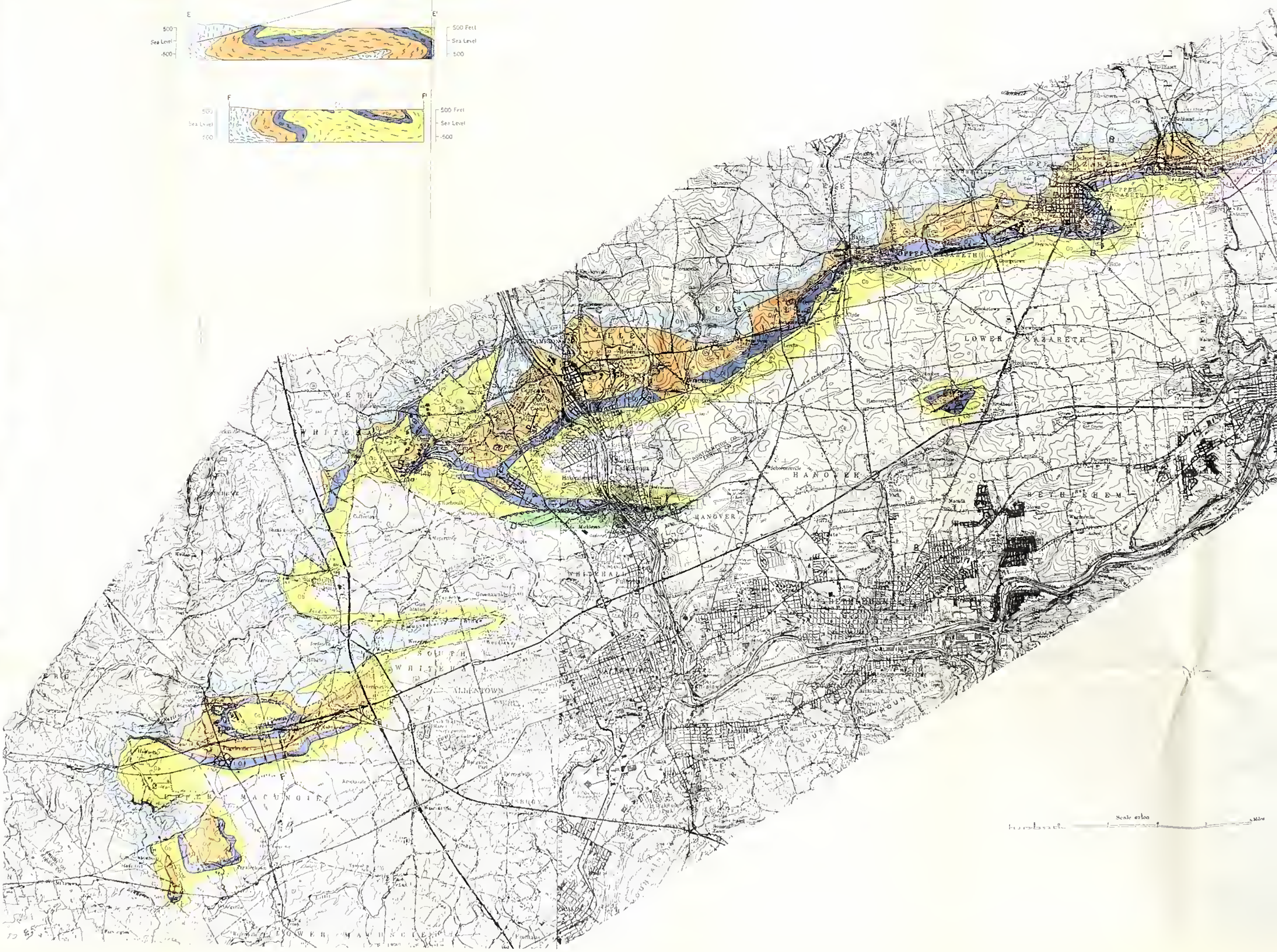

Geology by W. Cullen Sherwood, 1961

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